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Use Of Landsat Satellite Imagery To Identify The Salinization Of Soil Due To Brine Spills In Northwestern North Dakota

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USE OF LANDSAT SATELLITE IMAGERY TO IDENTIFY THE SALINIZATION OF SOIL DUE TO BRINE SPILLS IN NORTHWESTERN NORTH DAKOTA

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Abstract

Oil and gas development in northwestern North Dakota, has resulted in the drilling of more than 32,000 wells and produced large volumes of salt water (brine). Brine spills can have negative impacts on plant and water resources. This research evaluated the detection of brine spills in Bottineau County, North Dakota using Landsat imagery and the Canopy Response Salinity Index (CRSI). The CRSI uses ratios of near-infrared and infrared bands from Landsat imagery. Spill data for Bottineau County from 1975 to 2017 were collected from the North Dakota Department of Health for analysis of spill volume, number of spills, and timing of the spills. A total of 24 Landsat TM, ETM+ and OLI sensor images were collected and analyzed for the month of June from 1982 through 2017 using ENVI 5.3 and Arc GIS 10.6. Pre and post spill CRSI values at 197 known spill locations were evaluated using least squares linear regression analysis and the non-parametric Mann-Kendall and Kendall’s Tau tests. Regression analysis showed significant ($p<0.05$) decreases in CRSI values at 53.9% spill locations, while 29% showed no change and about 17.1% showed an increasing trend. The non-parametric Mann-Kendall and Kendall’s Tau analysis showed decreasing trends at 60% of the spill locations, while 30 % showed no change and 10 % showed an increasing trend. The results show that decreased CRSI values can be used to identify brine spill locations. Further study will require analysis of soil sampled from the identified local areas to confirm the chemical constituents of the soil and the source of salinity.

Chapter 1
Introduction

1.1 Background

Heightened soil salinity is a significant problem all over the world (Hillel 2000) because it disturbs the local environment, damages ecological systems, and lowers and limits crop productions by permanently damaging soil (Doll et al. 1985; Doll 1989; Lauer, Harkness and Vengosh 2016). In contrast to natural salinization resulting from the weathering of rocks and minerals, the human-induced salinity changes in soil due to oil well exploration, mining, deforestation, and overuse of chemicals in farming is of significant concern (Doll et al. 1985; Bluemle 1985; Hillel 2000). This research examines the feasibility of using economically affordable and readily available Landsat remote sensing imagery as a primary tool to detect brine spills near oil well facilities in northwestern, North Dakota. The secondary objective of this study is to bring environmental awareness by preventing contamination of farmlands and further damage to wetlands, aquatic reserves, and forestlands as a result of anthropogenic soil salinity.

1.2 Oil Exploration Impacts on Soil Salinity in Northwestern North Dakota

Brine spills resulting from oil exploration activities have caused an emerging concern in North Dakota, an agrarian state. Crude oil exploration and related drilling activities in this region produce large volumes of gas (flare gas) and mixed liquid co-products. The extracted sub-surface liquids are primarily saltwater (brine), fracking fluids, and crude oil. These liquids are under pressure and could be separated by a phase-separation process consisting of a series of pressure vessels. The brine and other residual components of the liquid phases other than the hydrocarbons or oil are disposed of in accordance with the according to the state and federal regulations and guidelines. The disposal procedure is required to be strictly adhered to due to significantly higher salt concentrations in the brine (North Dakota State Century Code 2013). Brine spills occur during oil production activities at drilling facilities. The leading causes of the spilling are (a) seepage from the old brine dumping pits onto the surface and sub-surface soils; (b) old, rusted, ruptured, broken pipelines; and (c) aged infrastructure at well sites and inadequate spill control strategies. Brine spills are known as “contained” if the spilled brine remains within the oil well pad or containment areas, and “non-contained” if the spill extends anywhere outside the protected boundaries of a pad (Doll et al. 1985; LeFever and LeFever 2005; Gleason et al. 2014; EERC 2015). Non-contained brine spills can spread over the surface and through the porous sub-surface. Many studies have shown that spills rapidly alter the soil’s physical properties and soil salinity beyond prescribed levels in farmlands and vegetation areas (Doll et al. 1985; ND Oil and Gas Division 2017). Many brine and crude spills in North Dakota are under-reported, not reported, or self-reported with inaccurate facts because of loopholes in the existing environmental regulation (Springer 2018). Such human-induced salinity issues on farmlands are found to be common in northwestern North Dakota (Doll et al. 1985; Doll 1988; Merrill et al. 1990; Leskiw et al. 2012).

The brine production depends upon existing geology, climatology and local topology of oil well exploration areas, depth of drilling, and extraction of raw petroleum crude. North Dakota oil wells produce between three and 18 barrels of brine per single barrel of crude oil. In general, for one barrel of crude oil production, approximately seven to ten barrels of brine is produced as a byproduct (EERC 2015; ND Studies 2017). The produced brine or fracking fluid is a concentrated form of salt water, which can be ten times higher in salt concentration than that found in ocean water. Currently, North Dakota Bakken formation oil production exceeds 1 million barrels per day, which produces a massive volume of brine (USGS 2013; EERC 2015; ND Oil and Gas Division 2017). Also, data from western North Dakota (Iampen and Rostron, 2000) show brine having significantly higher values of electrical conductivity (EC), which exceeds 200 deciSimmens/meter, total dissolved solids (TDS) around 100,000 parts per million and Sodium Adsorption Ratio (SAR) of more than 350. The sodium ion is a common natural dispersant in the soil as opposed to the calcium, magnesium, aluminum, and, hydrogen ions that promote flocculation or sticking of soil together as aggregate in structured soil. The excessive concentration of sodium ions creates a condition where soil particles behave as individual particles and not as aggregates of soil as required for the movement of plant roots, air, and, water through the structured soil. The solvent with excessive sodium ion thus causes swelling and dispersing effects on farmland soils, mainly if the total flocculated salts level in soils fall below the threshold limit. The soil affected by brine spills is thus rendered useless for farming, and the soil remediation is an expensive process.

Soil analysis results have shown that brine-contaminated farmlands and vegetation zones near oil wells predominantly consist of sodium chloride (NaCl) and magnesium chloride ($MgCl_2$) compounds (Doll et al.1985; Doll 1988; Lauer, Harkness and Vengosh, 2016). It is observed that excessive salt uptake in the plant grown on the brine-impacted soil interferes with the photosynthesis process in the plant. In addition, soil dispersion based challenges, such as water and nutrients movement in the soil and in the plant (through reduced osmotic potential) have observable impacts such as plant dehydration, yellowing due to reduced nutrient uptake and a loss of the ability to generate energy required for sustained growth, resulting in plant death (Meehan et al. 2017). It is observed that the salinity impacted soils result in creating barren patchy land and drought-type situations (Läuchli and Grattan, 2007b; Meehan et al., 2017). At an early growth stage in the plant, the reversed osmotic effect damages the plant growth by declining the seeds germination process (Seelig 2000; Läuchli and Grattan, 2007b; Meehan et al., 2017).

The studies of the impact of brine spill on the physical properties of soil and its effect on farmlands, forests, grassland, and wetlands have been conducted by Hansen et al. 2006; Läuchli and Grattan 2007a; and Läuchli and Grattan 2012b. These compelling studies suggest that brine spills from oil exploration in northwestern North Dakota are of significant environmental concern because of their adverse impact on local crops and vegetation.

The most reported brine spills include spill during brine transportation by tanker trucks, leaking old and worn out pipelines, and seepage from the old surface and sub-surface dump sites. Officially, since 1975, brine and crude spills are reported using self-reporting forms provided by the North Dakota Department of Health (NDDH 2017). Oil well operators are required by law to file spill reports, not contained and non-contained forms near the respective well sites. These reports provide a spill location using to Public Land Survey System (Section, Township, and Range).

According to the NDDH (2017) data, the state has experienced approximately 3,900 reported brine spills. In the current study area of interest, the farmers of the Bottineau County have reported 537 brine spills since 1975. These spills are reported near vegetation and farmland areas specifically farmlands adjacent to the oil wells. The largest brine spill in Bottineau County was 0.33 M liters (2,100 barrels) in September 2004 (Lauer, Harkness and Vengosh 2016; NDDH 2017).

Brine contaminants found near oil wells contain salt ions of sodium, chloride, and bromide along with radioactive isotopes and other trace elements (Doll et al. 1985; Doll 1988; Murphy 1988; Lauer, Harkness and Vengosh 2016). The exact land and wetland areas damaged because of brine spills is uncertain since these brine spills are self- and under-reported. Also, investigations are incomplete, in terms of determining the areas of extent and coverage of the contaminated zones (Doll et al. 1985; Preston, Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). Previous research efforts to evaluate soil salinity are mainly ground-based studies that rely upon previous models or interpolation of risks, hazards, and pollution-based analysis. Few studies in the literature document remote sensing studies in terms of understanding how brine spills impact locations, the extent of the impact, and time-based analysis in terms of pre- and post-vegetation impacts from salinization. (Doll et al. 1985; Ibrahim 1987; Scudiero, Skaggs and Corwin 2015; Lauer, Harkness and Vengosh 2016). However, this study may not separate natural salinity from the human-induced salinity from oil exploration activities, but certainly, with known brine locations and nearness to the oil well facilities, it should be possible to define the brine spills impacted zones. Previous studies have shown that brine sources near oil wells and adjacent to vegetation areas are the primary causes of land degradation because of human-induced salinity (Doll et al.1985; Preston, Chesley-Preston and Thamke 2014; EERC 2015, Lauer, Harkness and Vengosh 2016).

1.3 North Dakota Petroleum Development and State Regulations

The Williston Basin geological structure contains abundant oil and gas reserves and includes a portion of the Bakken geological formation that is the primary target of current oil and gas exploration in the region (Figure 1.1). The first oil well in this area was established in 1951 near the town Tioga, ND; and since then oil development in the state has significantly increased

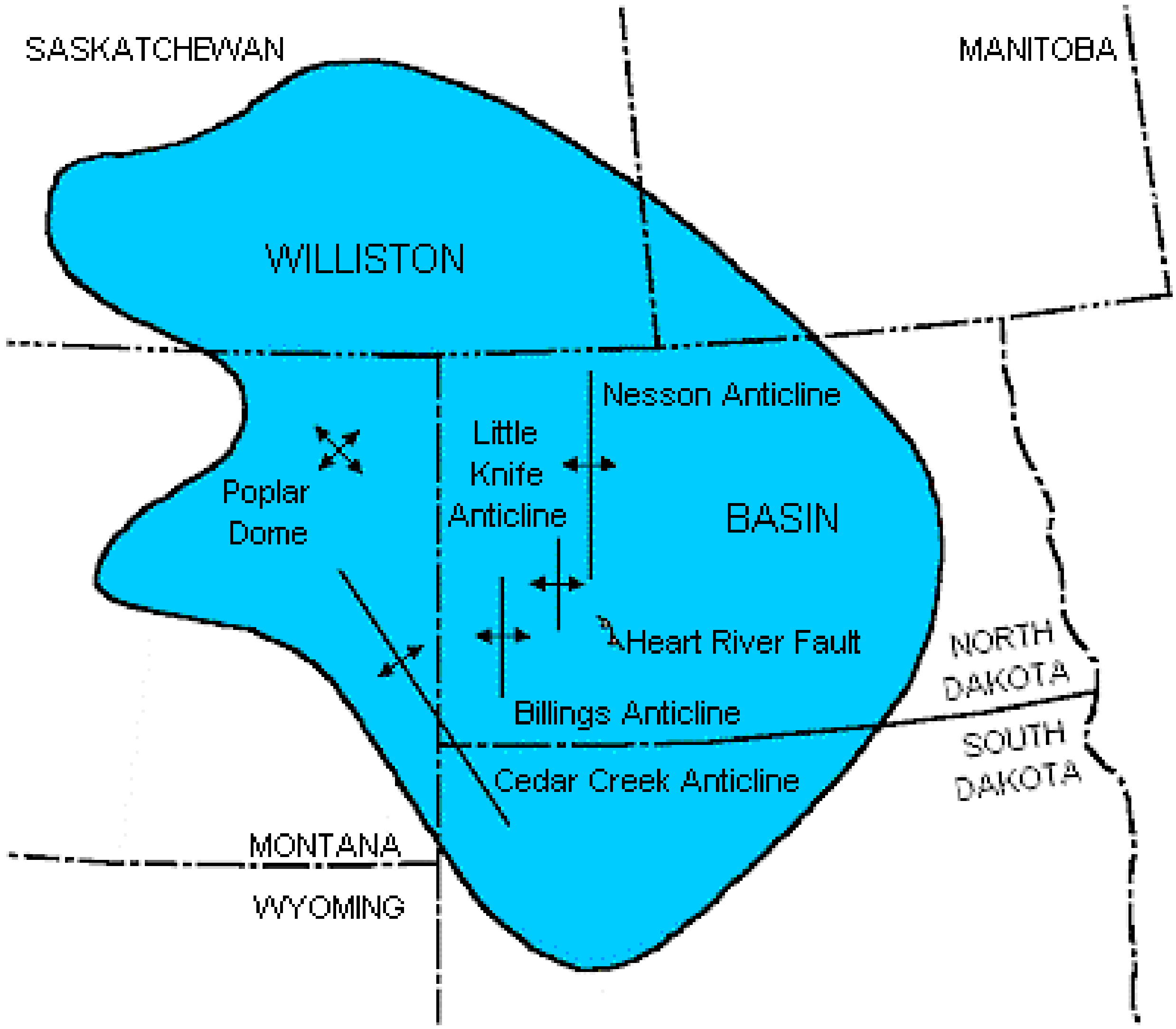

Figure 1.1: The extent of the Williston Basin with major North Dakota geologic structures shown (ND Oil and Gas Division 2017)

(Bluemle 2000) (Figures 1.1, 1.2). North Dakota field petroleum production has grown significantly since 1980, as shown in Figure 1.2 (EIA 2018) Since the first oil development in North Dakota in 1951, the state has continued to increase production and is currently second after Texas (Headwater Economics 2014; EIA 2018).

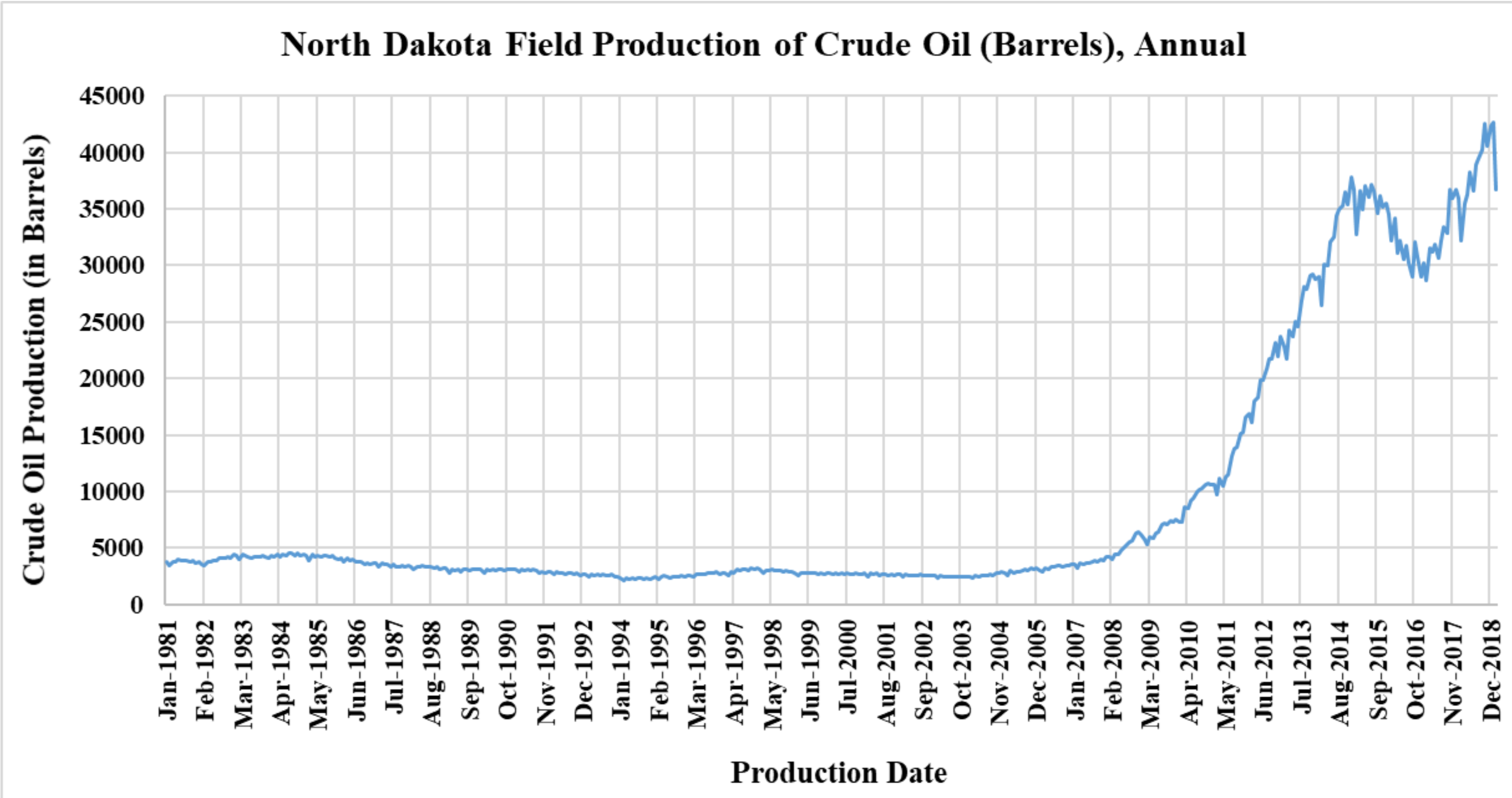

Figure 1.2: North Dakota Field Production of Crude Oil, Annual (Data Source: EIA 2018).

The oil and gas industry, in North Dakota, contributes in terms of massive tax revenue and job growth, thus enriching the state's economy (Headwater Economics 2014). The State of North Dakota taxes oil operators per the volume of oil or gas produced per barrel of oil or 1,000 cubic feet of natural gas requiring the oil well operators to pay two production-based taxes in a combined form of 11.5%, which brings petroleum revenue in the state (Headwater Economics 2014). Following the most recent oil boom in North Dakota, the number of oil wells in the state exceeds 32,000 (Figures 1.3 and 1.4) (Bluemle 2000; ND GIS Hub Data Portal 2017; NDDH 2017; EIA 2018). However, due to increasing oil well exploration activities, the state is experiencing increase the in brine and crude spills (Lauer, Harkness and Vengosh 2016; NDDH 2017).

Thus Oil well drilling and fracking can produce 477 to 1590 M liters (three to ten million barrels) of brine or salt water per day (Figures 1.1, 1.2) (Doll et al. 1985; Bluemle 2001; ND GIS Hub Data Portal 2017; EERC 2015; NDDH, 2017).

Historically, in North Dakota from 1951 to 1974, saltwater or brine was disposed of in unlined designated dumping sites known as "brine dumping pits." These sites varied in the size and scale in terms of measurements at different places, however approximately these dumping pits were 14 x 18 meters (45 x 60 feet) up to 27 x 55 meters (90 x 180 feet) in width and length and 1 to 3 meters (4 to 9 feet) deep (Bluemle 2000; Murphy et al. 1983; Murphy and Kehew 1984; Beal et al. 1987; Murphy 1988; Reiten and Tischmak, 1993; Thamke and Craigg 1997). As a consequence of this unlined dumping in open space, leachate chemicals generated because brine contamination exceeded up to 150 meters (492 feet) area and 20 meter (66 feet) depth with steady-state salt migration (U.S. EPA, 1977; Murphy 1983; Murphy and Kehew, 1984, Murphy et al. 1988). Thus, most of these unlined pits started seeping to the surface and sub-surface and contaminated nearby farmlands with salinity. To counter this adverse effect, in 1974, new state brine disposal regulations were enacted to contain the farmland pollution because of leakages from brine pits that required the oil companies to underline these dumping pits with plastic liners before disposing the brine and crude spills (EPA 1977; Beal et al. 1987; Murphy 1988; Reiten and Tischmak 1993). However, these regulations proved inadequate and failed in terms of curbing brine contaminations since many of these dumping sites started leaking through plastic liners creating non-degradable plastic pollution (Doll et al. 1985; Murphy and Kehew 1984; Beal et al. 1987; Reiten and Tischmak 1993; Thamke and Craigg 1997). The same brine seepage issues continued in spite of plastic and clay liners that added more problems to the existing problem instead of solving it (U.S. EPA, 1977; Murphy and Kehew 1984; Doll et al. 1985; Murphy 1988; Beal et al. 1987; Reiten and Tischmak 1993; Preston and Thamke 2014; ND Oil and Gas Division 2017 2017).

The number of brine ponds in North Dakota is estimated at approximately 2,000 to 3,000, with 121 brine dumping sites in Bottineau and Renville counties (U.S. EPA, 1977; Doll et al. 1985; Murphy and Kehew 1984; Bluemle 1985; Beal et al. 1987; Murphy et al. 1988; VanderBusch 2017). These brine pits have contaminated more than 5.9 million m^2 (1,450 acres) of land with 0.05 million m^2 (12 acres) average per site. After assessing these issues, to reduce further damage caused by brine and oil spill pollution, the State of North Dakota introduced along with the U.S. Environmental Protection Agency (EPA), new guidelines in 1994. These newly introduced guidelines were required by all oil exploration companies to protect the local environment, farmlands, vegetation, and local aquatic resources (Reiten and Tischmak 1993; EPA (UIC) 1999; North Dakota State Century Code 2013; Lauer, Harkness and Vengosh 2016).

The brine disposal guidelines are:

1. Dispose of the produced brine water by truckloads or through pipelines at the government approved designated disposable areas or sites.
2. Inject the produced brine water into deep geological formations at the designated depth as per the guidelines by EPA; where through injection into deep geologic formations, saltwater is far and eliminated from surface water resources and aquifers.
3. Treat the produced water and make it domestically usable by removing excessive salts and harmful pollutants and then only oil well companies can release treated water in the domestically available form to local reservoirs.

Also, in 2012, The State of North Dakota established strict rules barring the use of reserve pits for storing fluids produced during oil well completion (North Dakota Century Code 2013). Presently, the most commonly used disposal of produced brine is through injection into deep geologic formations where saltwater is far and eliminated from surface water and resources and aquifers. In addition, about 56,327 kilometers (35,000 miles) of pipelines have been established in the region for the disposal of brine fluid (EERC 2015; ND Oil and Gas Division 2017).

1.4 North Dakota State and Bottineau County, Agricultural Significance

From the perspective of this research, it is essential to understand the significance of agriculture to North Dakota and the study area, Bottineau County. The State of North Dakota is considered as one of the top five farming and agricultural based states of the U.S. with vast resources of horizon touching hectors of lush green farmlands, prairie lands, grasslands, wetlands, and local fishing aquatic reserves with the substantial revenue generating farming agribusinesses (USDA, 2017). The principal crops of North Dakota include durum wheat, barley, spring wheat, oats soybeans, beetroots, potato, canola, and sunflower (USDA, 2017). According to the USDA (2017), North Dakota ranked number one in the producer of dry edible beans, pinto beans, navy beans, canola, flax seeds, sunflower oil, durum wheat, spring wheat, and honey. Also, the state ranked second for sunflower and all types of wheat productions followed by barley, lentils, oats, peas, sugar beets, safflower, hay alfalfa, potatoes, corn, soybeans, and winter wheat in the third rank (USDA, 2017). Table 1.1 shows farm product yield data of Bottineau County, showing that the county is an agriculturally diverse and productive farming area.

Table 1.1: Bottineau County Agricultural Products

Bottineau County Agricultural Products		
Products	Tons/Acre	Kilograms/Hectare
Spring Wheat	1.3	2,914.2
Alfalfa Hay	1.9	4,259.2
Dry Edible Pea	1.4	3,138.4
Flax Seeds	0.4	896.7
Canola	1.0	2,241.7
Corn Yield	2.6	5,828.4

This little information suggests the significance of these areas in terms of agricultural production and agribusiness (USDA 2017).

1.5 Statement of the Problem

This research explores the soil salinity issues in the northwestern part of North Dakota, Bottineau County specifically, using remote sensing as a measuring tool. This study has been conducted from years 1982 to 2018 using Landsat imagery from Landsat 4, 5, 7, and 8 (Landsat TM, ETM+, and OLI). There has been limited research done in estimating soil salinity using remote sensing as a primary tool. North Dakota is one of the most crucial farming states of the U.S. (USDA, 2017). The state has been facing many challenges lately, with increasing brine and crude spills. The oil boom is steadily rising with more than 32,000 (NDDH 2017) oil well facilities in the state since the 1950s making it one of the most revenue generating industry (Bluemle 2000; Bluemle 2001; Headwater Economics, 2014; NDDH 2017). The brine leakages through the old historical brine dumping pits and ruptured brine transportation pipelines seep through surface and subsurfaces ultimately damaging local reservoirs, croplands, and wetlands. These issues have contributed to the degradation and deterioration of local farmlands of North Dakota. This research is an extended attempt to understand the soil salinity impacting the farmlands of North Dakota using Landsat imagery.

1.6 Research Objectives

Analysis of timing and quantity of brine spill data for Bottineau County, North Dakota

Use of Canopy Response Salinity Index (CRSI) with Landsat 4, 5, 7, and 8 (Landsat TM, ETM+, and OLI) imageries from years 1982 to 2018 June month to quantify saline soils in Bottineau County, ND, and relationship to brine spills.

However, the first clear image from June for this research starts in 1986 due to image clarity issues in Landsat images from 1982 to 1985. This research is aimed to quantify in terms of the damaged of farmland acreage of areas assessment using CRSI values and time-based analysis to understand in terms of the soil degradation and remediation process with respect to time.

Chapter 2
Literature Review

2.1 Natural Soil Salinity

A saline soil contains a high level of soluble salt, which impacts plant growth. Soil salinity is measured in electrical conductivity (EC and unit deciSimmens/meter) (Hillel 2005). United States Department of Agriculture (Richards 1954) classify soil salinity with an electrical conductivity (EC) greater than four deciSimmens/meter (dS/m) and Sodic with a Sodium Adsorption Ratio (SAR) greater than 13, as measured in the saturated paste. Saline-sodic soils possess EC greater than four dS/m and SAR greater than 13 while Sodic soils have EC less than four dS/m and SAR greater than 13 in their saturated paste (Richards 1954; USDA, 2017).

Mainly there are two types of soil salinity observed in northwestern North Dakota; 1) natural soil salinity, and 2) Human-induced or anthropogenic soil salinity (Doll et al., 1985; Hillel 2005; Shrivastava et al., 2015). Natural salinity is formed from geologic parent materials, mineral weathering, climatic and hydrological conditions, and is mostly a concern in arid and semi-arid regions (Hillel 2005; Shrivastava et al., 2015). Also, factors such as irrigation, soil type, local climate, and water usage, and drought conditions can contribute to soil salinity. In parts of northwestern North Dakota, soil chemistry of surface and near-surface sediments consist of the high level of clay. Soils and sediments are comprised of 10% of sand while silt and clay contents range from 1.4% to 89.8%, with a mean of 22.4% (NRCS, 2017). Bottineau consists of very deep, well drained, moderately slowly permeable soils in loamy glacial till on uplands and slopes ranging from 0 to 25 percent. The mean annual temperature is 4.4℃ (40˚F), and the mean annual precipitation is 45.7 cms (18 inches) (NRCS, 2017). In cropland areas, clay soils have an increased proneness to swelling in the surface and subsurface with dispersion where individual soil particles separate from one another in the presence of high levels of salinity (Seelig 2000; Hillel 2005; Läuchli and Grattan, 2007b; Shainberg and Singer 2011). Naturally saline land contains sulfate ion compounds such as $NaSO_4$, $CaSO_4$, and $MgSO_4$ in North Dakota (Doll et al. 1985; Doll 1988; Seelig 2000; Preston, Chesley-Preston and Thamke 2014.).

2.2 Human-Induced Soil Salinity and It is Impacts in North Dakota Farmlands

Human-induced or anthropogenic soil salinity is caused by activities such as oil well excavation, drilling, mining activities, and deforestation of the land. In North Dakota, one of the primary reasons for the anthropogenic salinization happens because of oil well exploration activities (Doll et al. 1985; Hem et al. 1985; Shrivastava et al. 2015). Despite all available knowledge, the problem of human-induced soil salinity has increased at a significantly higher level in the northwestern part of North Dakota (Lauer, Harkness and Vengosh 2016). There are many known brine and crude spill incidents in northwestern North Dakota, which have alarmed local farmers, residents, geologists, scientists, and environmentalists because of environmental damage affecting the future of residents and farmers and thus unbalancing the local ecological system (Lauer, Harkness and Vengosh, 2016; NDDH 2017). High salt contents in water and soil can cause water stress and ultimately result in dying of crops or significantly reduced the crop. As a result, crop loss, acidification, nutrient depletion and organic matter reduction in crops, ecological and aquatic imbalance of wetlands areas have grown significantly in these areas (Seelig 2000;LeFever and LeFever 2005; Läuchli and Grattan, 2007b; Läuchli and Grattan, 2012b; EERC 2015; EERC 2016; Meehan et al. 2017). Because of this salinization effect, earlier fully functioning farmlands have resulted in underdeveloped crops with yellow and burnt looking leaves, small and restricted roots with a low yield of farm produce creating a significant economic loss in the farming industry (Seelig 2000; Läuchli and Grattan, 2007b; Läuchli and Grattan 2012b; EERC 2015; Meehan et al. 2017).

2.3 Soil Chemistry of Brine Spills Affected Areas in North Dakota

Oil and gas wells produce brine or saltwater as a byproduct. This brine, depending upon the depth and areas, can be moderate to high in salinity between 5,000 to 270,000 milligrams per liter (mg/L) in total dissolved solids (TDS). These dissolved solids are mostly sodium, magnesium and calcium chloride and in small amounts bromide ion compounds. However, the brine is defined as "saltwater contents more than 35,000 mg/L (milligrams per Liter) or (0.29 pounds or 4.7 ounces per gallon) "total dissolved solids" (TDS) (Hem et al. 1985; Kalkhoff et al. 1993; Dresel and Rose 2010). In the terminology of oil and gas production this brine is a byproduct of the drilling or fracking process and production, and that is why it is popularly known many names such as "frack fluid" or "oil and gas brine" or "produced saline water "or "sedimentary basin brine" (Hem et al. 1985; Kalkhoff et al. 1993; Dresel and Rose 2010).

It is essential to know the chemistry of soil and brine-affected areas of this region, where the brine produced during oil drilling prove the claim that the brine source indeed came from oil well exploration activities can be proven through the chemical analysis of the salinity of the farm soil. The data analysis of brine spills near oil and gas facilities show a distinctly different chemical analysis of salinity than the naturally salty zones in North Dakota. The naturally saline soils in North Dakota and Bottineau County contain mainly Sulfate ions (SO_4^{2-}) salt compounds while Brine spills affected soils adjacent to the oil and gas facilities areas contain mainly soluble inorganic compounds of chloride (Cl^-) and bromide (Br^-) ions such as Sodium Chloride (NaCl), Sodium Bromide (NaBr), Magnesium Chloride ($MgCl_2$) and Calcium Chloride ($CaCl_2$) along with small amount of bicarbonate (HCO_3^-) and Sr (Strontium) trace elements amount (Doll et al.

1985; Peterman et. al., 2012; Preston, Chesley-Preston and Thamke, 2014; Lauer, Harkness and Vengosh 2016.). Thus it is proven that high concentrations of chloride (Cl^-) ions could be linked with oilfield brine spills (Doll et al. 1985; Peterman et al. 2012; Lauer and Thamke 2014). However, the Sodium ion (Na^+) is not a determining factor as a measurement of any salinity impact since the sodium ion is universally present in all saline soils, whether natural or human-induced (Doll et al. 1985; Doll 1988; Seelig 2000). Distinct differences in the chloride ion (Cl^-) levels in soil could be related to brine spills versus natural soil salinity (Doll et al. 1985; Doll 1989; Lauer and Thamke 2014). In addition to that, high concentrated brine spills in farmlands increase the concentrations of inorganic compound ions such as sodium (Na^+), magnesium (Mg^+), calcium (Ca^{2+}), potassium (K^+), chlorine ($Cl^–$), sulfate ($SO_4^{–2}$), bisulfate ($HSO_3^–$), nitrate (NO_3^-) and carbonate ($CO_3^{2–}$) and alters the physical properties of soil. As a result excess ionization in these plants may change the internal biochemistry process by upsetting the ionic transport within the plant cell, especially in newly growing young crops and plants (Doll et al. 1985; Läuchli and Grattan 2007a; Läuchli and Grattan 2012b). Hence, concentrated salts in farmlands increase osmotic potential between plant roots and soil water. Thus, plants try to balance and compensate for the increase in osmotic potential by spending energy to increase internal solute absorptions (Hansen et al. 2006). Therefore, plants spend more time and energy per unit of water processing high salinity salts (Table 2.1; Doll et al. 1985; Läuchli and Grattan 2007a; Läuchli and Grattan 2012b). This phenomenon reduces the overall production of crops, severely damaging the economic sustainability of the local agricultural industry. Also, high content of salt in farmland may also cause waterlogging issues because of the instability of internal drainage systems and clogging of the surface due to dispersed soil clay particles which overall creates an unsuitable environment for the plant growth and development (impact on crop yield as a function of electrical conductivity corresponding to different level of soil salinity. (Table 2.1; Quirk 2001; NRCS 2017).

Table 2.1: Impact on crop yield as a function of electrical conductivity corresponding to a different level of soil salinity.

Soil Salinity Level	Electrical Conductivity (dS/m)	% Yield
Non Saline	0-2 dS/m	100
Slightly Saline	2-4 dS/m	70-80
Moderately Saline	4-8 dS/m	40-70
Severe Saline	8-16 dS/m	0-40
Very Severe Saline	> 16 dS/m	0

2.4 Sources of Soil Salinity near Oil Fields in Northwestern North Dakota

Today, most of these old, unlined reserve pits are the primary cause of contamination according to the research studies, however, lately other sources of contamination include old infrastructure corroded pipelines, ruptures in existing produce water transporting and crude pipelines, mishandlings or leakages during fluid transportation by trucks, mishandling during proper disposal of brine spills (Doll et al. 1985; Lauer and Thamke 2014; Lauer, Harkness and Vengosh 2016). Brine spills in North Dakota are self-reported, and the timeliness of the reporting and accuracy of the amount spilled may not always be accurate. Furthermore, spill locations are reported to the quarter section or quarter-quarter section, which can introduce a location error of up to 64,700 m^2 (160 acres).

2.5 Remediation and Reclamation of Salinity Impacted Farmlands

Remediation of saline soils is a lengthy and slow process. The State of North Dakota has approached the remediation and reclamation of brine contaminated farmlands at various levels, emphasizing surface and sub-surface level water resources. The most used and tried method is

Harkness, and Vengosh (2016). However, this method is an expensive and ineffective process for the removal of brine affected soil through the excavation (Doll et al.1985; Doll 1988; Lauer, YEAR) in larger farming areas.

In order to remove excess salt and increase permeability in the soil, the water leaching of Na^+ is encouraged to promote regrowth in the soil. Farmers generally use a calcium-based mineral such as gypsum ($CaSO_4$) to increase permeability, which replaces sodium ions with calcium (Doll et al. 1985; Merrill et al.1990; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). This cation exchange process increases the porosity of soil and thus helps the plant regrowth process. Sodium ions leaching from the upper parts of the soil can be transported to wetland zones via shallow groundwater (Doll et al. 1985; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). Other salted land remediation techniques include incorporating various organic materials such as hay, sand, manure, and fertilizers in the existing soil. Also, tillage, proper irrigation channels, a better drainage system to enhance lateral transport and prevent polluted water and phytoremediation are mainly mentioned in many scientific kinds of literature (Doll et al. 1985; Preston, Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016).

2.6 The Most Common Visible Indicators of Soil Salinity

The most commonly identifiable indicators of the soil salinity and the presence of excess salts in the ground and farmland (Richards 1954; USDA 2017).

Table 2.2 shows the most common visible indicators of soil salinity.

Table 2.2: The most common visible indicators of soil salinity.

1	Bare and scalded farmland
2	Salt crust presence in brickwork
3	A significant change in crop quality
4	Roads with seepage due to leaking pipeline and aged infrastructures
5	Growing of salt-tolerant plants in areas
6	A white layer of crust on the soil
7	Corroded pipeline
8	The decline of vegetation such as trees, grass, shrubs

2.7 Methods Used to Identify Soil Salinity

Many traditional methods have been used to classify brine contamination to surface water and shallow groundwater resources (Richards, 1954; Doll et al. 1985; USDA 2017). Table 2.3 shows the methods used to determine salt contents in soil. These geochemical methods are used since produced brine often modifies salinity and strontium isotope ratios in surface water and shallow groundwater. Also, geophysical methods are mainly relevant to determine surges in the pattern of the electromagnetic conductance of soil and shallow groundwater from brine.

Table 2.3: Methods Used to Determine Salt Contents in Soil (Richards 1954; USDA 2017).

Method 1	Preparation of saturated pastes and determination of saturation percentage
Method 2	Measurement of pH of the saturated paste
Method 3	Soluble cations
Method 4	Electrical Conductivity
Method 5	Chlorides
Method 6	Extractable and Exchangeable Cations
Method 7	Calcium Requirement

The following measures are required to conduct soil salinity assessment in the ground.

Measurements of salts in soil or water in farmland are as follows:

1. Trace salinity problem through waterways and catchments;
2. Determine the changes in the field over the period; and
3. Understand where the most salinity likely to happen through groundwater discharge

According to the U.S. Salinity Staff Laboratory, saline soils are defined by following standards (Richards et al. 1954; Allbed and Kumar 2013). Soils EC for the saturation extract.

1. (EC) > 4 DeciSiemens per meter (dS/m) at 25˚C (77˚F)
2. Exchangeable Sodium Percentage (ESP) < 15
3. pH (soil reaction) < 8.

2.7.1 Soil Salinity Classification

The units of soil salinity are essential to know as it shows the physical characteristics and classification of soil by its salinity levels. The unit used for the soil salinity is known as micro Siemens per centimeter (µS/cm). Soil salinity mainly expressed as an 'EC Unit, ' and salinity standards units are referred to as “DeciSiemens per meter” (dS/m). The extent and levels of salinity measurement through electrical conductivity (EC) known as a measurement of soil salinity (EC, dS m^{-1}) can be assessed using the below-given classifications (Richards 1954; USDA 2017).

Table 2.4: Classification of Saline Soils and Plant Growth (USDA 2017).

Types of Soil Salinity	**Electrical Conductivity (dS/m)**	**Effect on Crop Plants**
Non-saline	0-2 dS/m	Salinity effects insignificant
Slightly saline	2-4 dS/m	Yields of sensitive crops may be affected
Moderately saline	4-8 dS/m	Yields of many crops are affected
Strongly saline	8-16 dS/m	Only salt tolerant crops yield grow
Extremely saline	>16 dS/m	Only limited salt tolerant crops yield grow

2.8 Application of Remote Sensing Methodology as Brine Spills Assessing Tool

In the past, remote sensing data have been used intensively to identify and map salt-affected areas for precision farming and various other purposes (Robbins and Wiegand 1990). For soil salinity research, data acquired through Landsat image s, and LiDAR (Light Detection and Ranging) have been useful for understanding, mapping and monitoring soil salinity in different regions all over the world (Dwivedi and Rao 1992, Preston, Chesley-Preston, and Thamke 2014; Scudiero, Skaggs, and Corwin 2015; Lauer, Harkness and Vengosh 2016).

LiDAR uses light in the form of a pulsed laser to measure variable distances in more precise three-dimensional information with a high level of georeferenced accuracy (NOAA 2017). LiDAR can be possibly used in terms of determination locations of brine pits and ponds (NOAA 2017). However, the process has some limitations, such as producing a large data set, and in the ability to penetrate dense canopy areas.

Apart from that, investigations in North Dakota and the Bakken Formation regions are incomplete to assess and study the scope and scale of the contamination (Doll et al. 1985; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). Previously, few attempts have been made to assess these spill areas, and most of these study are ground-based and highly dependent on the modeling of interpolations of hazards and contaminated areas (Doll et al. 1985; Doll 1988; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). Also, earlier studies used aerial photographs to determine the location of buried brine pits and salt-affected soils in North Dakota (Doll et al. 1985; Bluemle 1985; Doll 1988). These ground-based studies did not present an in-depth time-based analysis of soil salinity in regards to pre- and post-brine spill time-based analysis in terms of land deterioration or reclamation of baseline soil salinity for farmlands adjacent to oil well facilities (Bluemle 1985; Murphy et al. 1988; VanderBusch 2017).

2.9 Identification of Brine Spills Using Landsat Imagery Bands

Multi-sensor remote sensing studies primarily use band ratios of visible to near-infrared and infrared bands for a successful way of measuring for classification of soil salinity, in terms of determining healthiness and unhealthiness of vegetation areas as compare to visible individual true color bands (Craigg et al.1998; Hick and Russell 1990). Many standard signature salt indexes have also been developed based on satellite imagery (Table 2.5, Ibrahim 1987; Scudiero, Skaggs and Corwin 2015; Scudiero et al. 2017).

Table 2.5: Vegetation and soil salinity indices used for soil salinity monitoring and mapping (Allbed and Kumar, 2013).

	Indices	Equation
1	Normalized Differential Vegetation Index	$\mathrm{NDVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R})$
2	Enhanced Vegetation Index	$\mathrm{EVI} = 2.5(\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + 6\mathrm{R} - 7.5\mathrm{BLUE} + 1)$
3	Soil Adjusted Vegetation Index	$\mathrm{SAVI} = (\mathrm{NIR} - \mathrm{R})/(\mathrm{NIR} + \mathrm{R} + \mathrm{L}) \times (1 + \mathrm{L})$
4	Ratio Vegetation Index	$\mathrm{RVI} = \mathrm{NIR}/\mathrm{R}$
5	Normalized Differential Salinity Index	$\mathrm{NDSI} = (\mathrm{R} - \mathrm{NIR})/(\mathrm{R} + \mathrm{NIR})$
6	Brightness Index	$\mathrm{BI} = \sqrt{(\mathrm{R}^2 + \mathrm{NIR}^2)}$
7	Salinity Index	$\mathrm{SI} = \sqrt{\mathrm{BLUE} \times \mathrm{R}}$
8	Salinity Index	$\mathrm{SI1} = \sqrt{\mathrm{G} \times \mathrm{R}}$
9	Salinity Index	$\mathrm{SI2} = \sqrt{\mathrm{G}^2 + \mathrm{R}^2 + \mathrm{NIR}^2}$
10	Salinity Index	$\mathrm{SI3} = \sqrt{\mathrm{G}^2 + \mathrm{R}^2}$
11	Salinity Index	$\mathrm{SI\text{-}1} = \mathrm{ALI9}/\mathrm{ALI10}$
12	Salinity Index	$\mathrm{SI\text{-}2} = (\mathrm{ALI6} - \mathrm{ALI9})/(\mathrm{ALI6} - \mathrm{ALI9})$
13	Salinity Index	$\mathrm{SI\text{-}3} = (\mathrm{ALI9} - \mathrm{ALI10})/(\mathrm{ALI9} + \mathrm{ALI10})$
14	Soil Salinity and Sodicity Indices	$\mathrm{SSSI\text{-}1} = (\mathrm{ALI9} - \mathrm{ALI10})$
15	Soil Salinity and Sodicity Indices	$\mathrm{SSSI\text{-}2} = (\mathrm{ALI9} \times \mathrm{ALI10} - \mathrm{ALI10} \times \mathrm{ALI10})/\mathrm{ALI9}$
16	Salinity Index	$\mathrm{S}_1 = \mathrm{Blue}/\mathrm{R}$
17	Salinity Index	$\mathrm{S}_2 = (\mathrm{Blue} - \mathrm{R})/(\mathrm{Blue} + \mathrm{R})$
19	Salinity Index	$\mathrm{S}_3 = (\mathrm{G} \times \mathrm{R})/\mathrm{Blue}$
20	Salinity Index	$\mathrm{S}_4 = \sqrt{\mathrm{Blue} \times \mathrm{R}}$
21	Salinity Index	$\mathrm{S}_5 = (\mathrm{Blue} \times \mathrm{R})/\mathrm{G}$
22	Salinity Index	$\mathrm{S}_6 = (\mathrm{R} \times \mathrm{NIR})/\mathrm{G}$

For the further advancement in this research in remote sensing areas for the future scope of the study, it would help to develop and identify the spectral signatures of the brine spills and incorporate to known discharge locations of oil and brine spills near oil well facilities to better define the spill locations and areal extents. (Shreshtha and Farshad 2008; Allbed and Kumar 2013).

The spectral analysis and band characteristics from Landsat 4, 5, 7, and 8 (Landsat TM, ETM+, and OLI) have been used as an essential aspect of understanding remote sensing data analysis.

Landsat 4, 5 (Landsat TM) have seven bands, Landsat 7 (Landsat ETM+) consists of eight bands, and Landsat OLI (Landsat 8) has 11 primary bands for analyzing reflectance spectrum, which can be used for various purpose such as farming, military intelligence, climate data analysis, cropland analysis, urban planning. In all Landsat imagery, the near infrared, or NIR, wavelength band spectrum is necessary for ecology and vegetation since healthy plant reflect much NIR.

At least 22 salinity indexes have been used by various researchers all over the world to determine the healthiness of the vegetation (Table 2.5). The CRSI index, primarily developed by Scudiero, Kaggs and Corwin at the U.S. Salinity Laboratory at Riverside University, California, is known as one of the most effective and successful salinity indexes to assess cropland healthiness since it gives a low error and more precise data of plant healthiness (Scudiero, Skaggs and Corwin 2015). Soil salinity detection using CRSI , NDVI (Normalized Difference Vegetation Index), and EVI (Enhanced Vegetation Index)were tested in the United States Salinity Laboratory, Riverside, California. The research team, after large ground truth data based on several independent sample analysis, cross-validation methods and salinity expert based quality assessment have come up with good fitted statistical model based salinity index known as Canopy Response Salinity Index (CRSI) (Scudiero, Skaggs and Corwin 2015; Zhang et al. 2015). The CRSI with better accuracy and precision of the EC predictions proved as the best-fitted model with $R^2 = 0.728$ and cross-validation $R^2 = 0.611$ (Scudiero, Skaggs and Corwin 2015; Zhang et al. 2015). The research team found this methodology as the least error methodology after comparing with different salinity indexes (Zhang et al. 2011; Scudiero, Skaggs and Corwin 2015; Zhang et al. 2015)

In the proposed CRSI index, for Landsat 4,5 and 7 (TM, ETM +) bands one, two and three are respectively known as blue, green and red and band four measures as the near infrared, or NIR (Table 2.6; Scudiero, Skaggs and Corwin 2015). While for Landsat 8 (OLI and TIRS) imagery, bands two, three and four are visible true colors, and band five are measured as the near infra-red, or NIR, respectively known as blue, green, and red and infra-red (Figure 2.7; Scudiero, Skaggs and Corwin 2015).

Table 2.6: Landsat 4 and 5 (TM) Band Information.

Landsat 4 and Landsat 5 TM (µm)	
30 m Band 1-Blue	0.45-0.52
30 m Band 2-Green	0.52-0.60
30 m Band 3- Red	0.63-0.69
30 m Band 4 - NIR	0.76-0.90
120*30 m Band 5 - SWIR 1	1.55-1.75
30 m Band 6 - TIR	10.40-12.50
30 m Band 7 - SWIR 2	2.08-2.35

TM Band 6 was acquired at 120-meter resolution, but products are resampled to 30-meter pixels. (USGS, 2017)

Table 2.7: Landsat 7 and 8 (ETM+ and OLI) Band Information.

Landsat 7 ETM + (µm)		Landsat 8 OLI and TIRS Bands (µm)	
30 m Band 1-Blue	0.45-0.52	30 m Band 1 - coastal/aerosol	0.44 - 0.45
30 m Band 2-Green	0.52-0.60	30 m Band 2 - Blue	0.45 - 0.51
30 m Band 3- Red	0.63-0.69	30 m Band 3 - Green	0.53 - 0.59
30 m Band 4 - NIR	0.77-0.90	30 m Band 4 – Red	0.64 - 0.67
30 m Band 5 - SWIR 1	1.55-1.75	30 m Band 5 – NIR	0.85 - 0.88
60*30 m Band 6 - Thermal	10.40-12.50	30 m Band 6 - SWIR 1	1.57 - 1.65
30 m Band 7 - SWIR 2	2.09-2.35	30 m Band 7 - SWIR 2	2.11 - 2.29
15 m Band 8 - Pan	.52-.90	15 m Band 8 – Pan	0.50- 0.68
		30 m Band 9 – Cirrus	1.36 - 1.38
		100*30 m Band 10 - TIRS 1	10.60 - 11.19
		100*30 m Band 11 - TIRS 2	11.50 - 12.51

* *ETM+ Band 6 is acquired at 60-meter resolution, but products are resampled to 30-meter pixels.*

* *TIRS bands are acquired at the 100-meter resolution but are resampled to 30 meters in delivered data product. (USGS, 2017)*

Chapter 3
Research Methodology

3.1 The Study Area: Northwestern North Dakota and Bottineau County

The study area is Bottineau County, North Dakota. Bottineau County currently has 2,488 oil well exploration facilities producing 15.4 million liters (131,535 barrels) of oil as per month. (Figures 3.1-3.4; EERC 2015; ND Oil and Gas Division 2017). The initial production of oil well facilities produced oil and saltwater ratio as 1:2, where produced brine was significantly high in number (Doll et al.1985; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016). Poorly managed legacy brine ponds, unlined dumping pits, buried brine pits have caused a high level of damage to the local farmland and wetlands as a result of leaking brine and other pollutants to the surfaces and subsurface since the 1950s in the Bottineau County (U.S. EPA 1977; Murphy 1988; VanderBusch 2017). The melting of snow and running brine water into surfaces and subsurfaces of farmlands, wetlands, forests and local reservoirs containing sodium (Na^+), chlorine (Cl^-) and bromine (Br^-) and bicarbonate (HCO_3^-) compounds have caused salinity and contaminated these areas (Doll et al.1985; Preston, Chesley-Preston and Thamke 2014; Lauer, Harkness and Vengosh 2016).

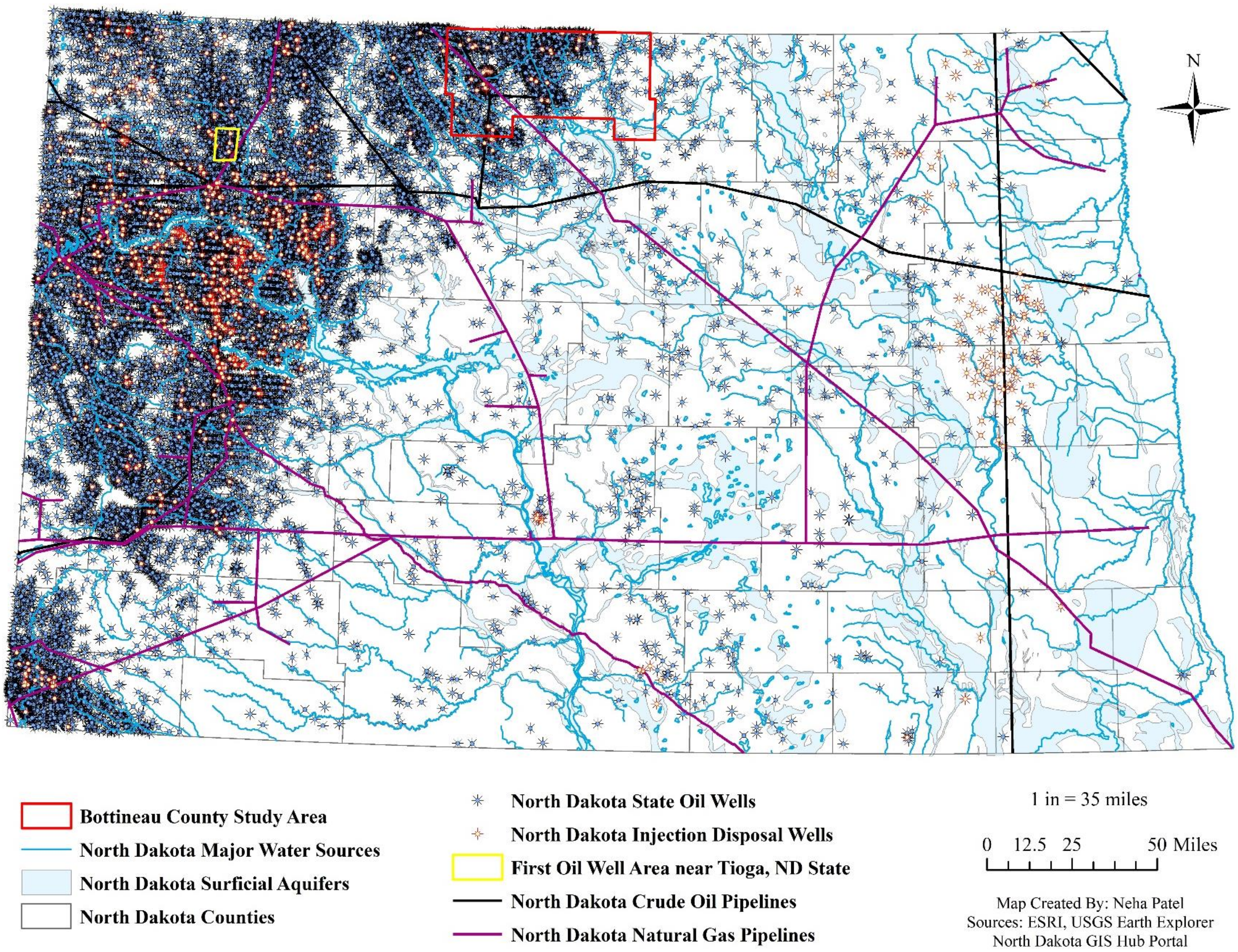

Figure 3.1: North Dakota State Oil Wells, Gas, and Crude Pipelines Facilities

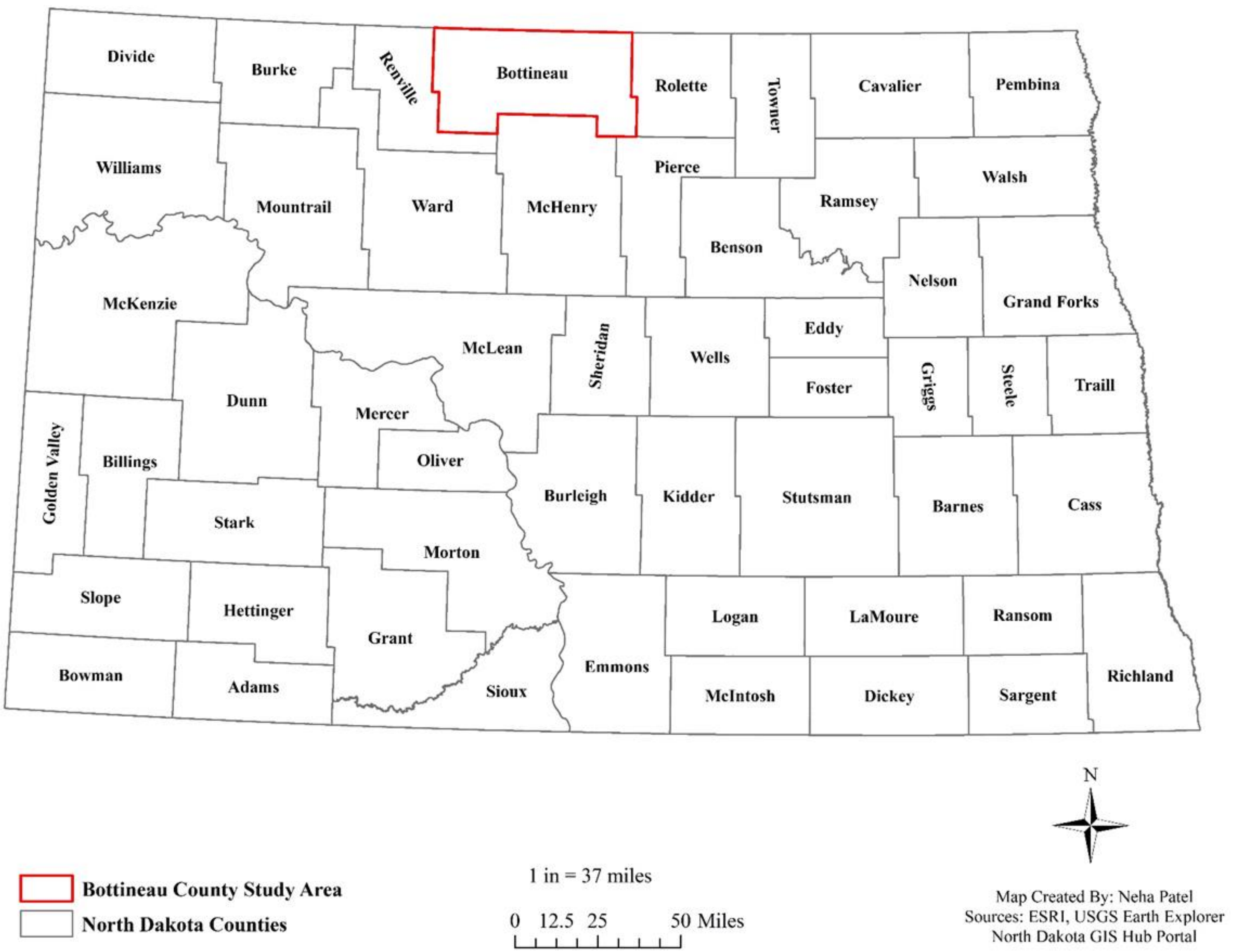

Figure 3.2: Study Area: Bottineau County, North Dakota.

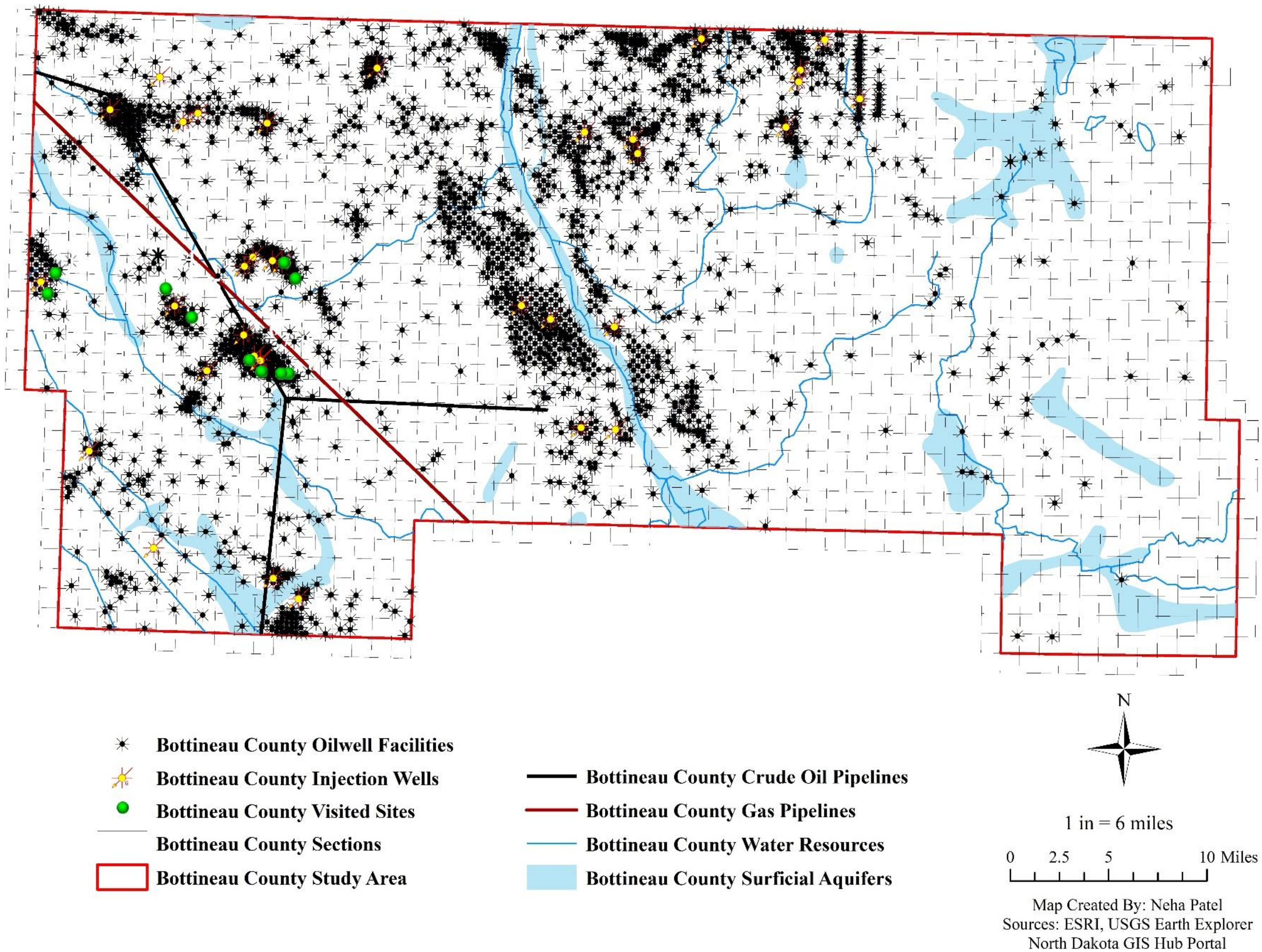

Figure 3.3: Bottineau County Oil Wells, Gas, and Crude Pipeline Facilities.

Figure 3.4: Oil Field Facilities in Bottineau County

3.2 Oil and Gas Reserves of Bakken and Three Forks Formations, Williston Basin and Northwestern Dakota

The Bakken, Three Forks, and Lodgepole formations are known for their oil reserves located mainly in North Dakota, Montana, South Dakota, and parts of Canada in Saskatchewan province (Figure 3.5). The Williston Basin is an overlapping geological structure continuous part of the above formations, which partly covers the northwestern North Dakota.

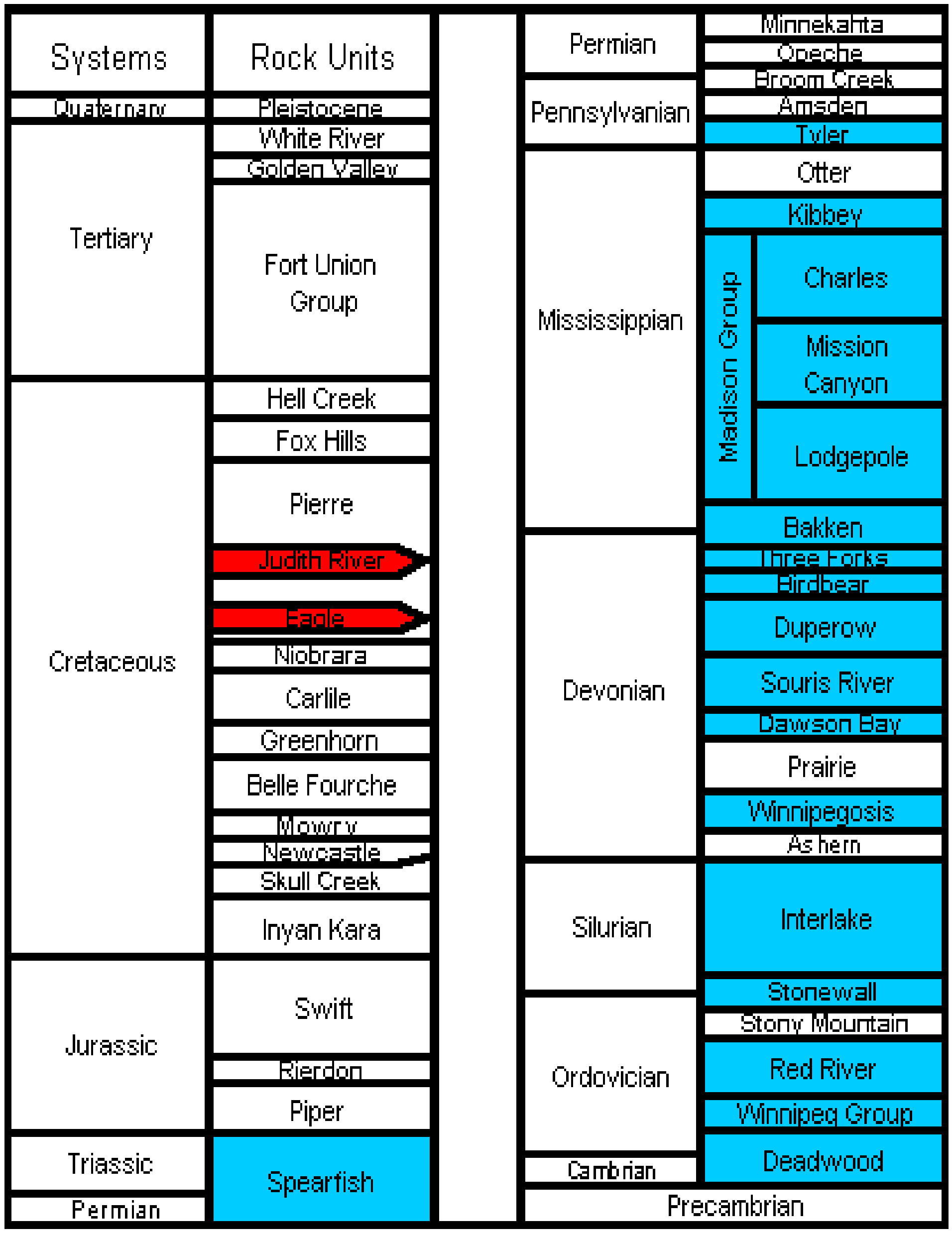

Figure 3.5: Generalized stratigraphic column for the Williston Basin with gas producing horizons shown in red and oil producing horizons shown in blue (NDGS, 2017).

3.2.1 Three Forks Formation

The Three Forks Formations is composed of anhydrides, silty dolostones and mudstones found below the Bakken formations. The formation consists of a maximum thickness of 82.3 meters

(270 feet) lying below the Bakken Formation. The Three Forks Formation reserves approximately 302 billion liters (1.9 billion barrels) (Figure 3.5; USGS 2013).

3.2.2 Bakken Formation

The Bakken and Three Forks formations are considered as one of the largest continuous oil reserves comparable to the oil producing nations to the world. As per the USGS (2013) data, the Bakken and Three Forks formations contain 1,176.5 billion liters (7.4 billion barrels) of oil, 189.7 trillion liters (6.7 trillion cubic feet) of natural gas and 84.3 billion liters (530 million barrels) of natural gas liquids that can be obtained from Bakken and Three Forks formations with the help of modern technologies (Pollastro, Roberts and Cook, 2013; USGS 2013). The Bakken formation Geological topography area covers the Three Forks and Bakken formations in the Devonian and Mississippian Period. Also, in the Mississippian Sub-Period, the Madison Group covers the Lodgerpole Formation, which is a continuous part of oil reserve extended up to the Bakken Formation in the Devonian Period (Figures 1.1 and 3.5; Pollastro, Roberts and Cook, 2013; USGS 2013).

The formation areas are arranged by the upper black shale area with sedimentary rocks, siltstones and sandstone and lower black shale with brownish mudstones. These areas are considered the source of petroleum crude oil and gas due to its extremely rich organic content presence. The structure of the Bakken Formation varies in thickness from east to the west side, and the maximum thickness includes 27.4 meters (90 feet) which are known as “Basin Center” on the east area of Nesson Anticline. The formation areas have low porosity and permeability, which makes the sedimentary rocks as tight solid formation. To recover crude oil, horizontal drilling techniques are mainly used where most oil wells are drilled horizontally along the tight rocky formations (Pollastro, Roberts and Cook, 2013; USGS 2013).

3.2.3 Willison Basin

The Williston Basin is 764.4 km (475 miles) north to south and 482.80 km (300 miles) east to west which falls in the northwestern North Dakota, Montana, South Dakota, Saskatchewan, and Manitoba. The basin center areas range up to 4,876.8 meters (16,000 feet) (Figure 1.3). The oil reserves exist in the basin, are accumulated in the form of "crude raw petroleum″ in geological formations of porous and permeable rocks; covered by nonpermeable, nonporous rocks in folded, or stratigraphically positioned in the faulted zones. Approximately 604.2 billion liters (3.8 billion barrels) oil and 13.3 trillion liters (470 billion cubic feet) natural gas can be obtained from the Williston Basin areas. Also, in these areas, well drilling process is done horizontally since the geology of the rocks have low porosity and low permeability, due to its solid tight formation in most case similarity as Bakken Formation areas due to similar issues. However, throughout times, the drilling technologies of oil well explorations and development in these areas have evolved, which help to recover crude oil and natural gas with utmost precision. The currently used horizontal drilling based on the local bedding planes, rock arrangements, and trapped hydrocarbons which is done by hydraulic fracturing under water and sand type materials are pushed under high pressure to create permeability in order for the better oil movement out of these tight sediment rocks (Pollastro, Roberts and Cook, 2013; USGS 2013).

3.2.4 The Data Collection Method

Brine and crude spill data were collected from the North Dakota Department of Health website (NDDH 2017). All collected spill data was sorted for the research area location in Bottineau

County using MS Excel software. Each incident ID report was examined for more detailed information such as the location of the spills, precise townships, range and sections, and second level of detail parceling for determining the accuracy of brine spill locations. The direction of the brine spills locations were provided in incident ID reports from years 1975 to 2017 as "quarter section" and "quarter-quarter section" in respective townships, range, and section areas. The formatted and sorted MS Excel data of Bottineau County detailed locations of "quarter section" and "quarter-quarter section" locations, which were converted into latitude-longitude locations using Earth Point file conversion data (Earth Point, Tools for Google Earth, Boise, USA, 2017). The brine and crude spills data for North Dakota State and Bottineau County were mapped on the base of latitude and longitudinal areas using ArcGIS 10.6 software (ESRI, Redlands, CA, USA).

3.3 CRSI Band Information and Equation

The CRSI salinity index is primarily used for the healthiness of vegetation lands to determine soil salinity impact in the areas. The CRSI formula consists of four band ratio of blue, green, red, and near-infrared (NIR). In remote sensing technology, to identify healthily and stressed croplands, wetlands and other forest-based vegetation; this band ratios formula of visible to near-infrared and between infrared bands, have been proven most effective for acquiring accurate results with minimum errors. CRSI values help to determine the quality of the cropland by distinguishing the type of land as healthy or unhealthy zones (Scudiero, Skaggs, and Corwin 2015; Lauer, Harkness and Vengosh 2016). Salinity Index values are measured using spectral band math analysis CRSI formula given below (Scudiero, Skaggs and Corwin 2015):

$$CRSI = \sqrt{\frac{(NIR \times R) - (G \times B)}{(NIR \times R) + (G \times B)}}$$

As per the CRSI band equation formula given above, the plants are “unhealthy” if CRSI values are ≤ 0.6 CRSI and plants are “healthy” if CRSI values > 0.6 and ≤ 0.99 (see Figure 3.6). Below shown, Figure 3.4 shows a simple graphic representation of CRSI salinity index values.

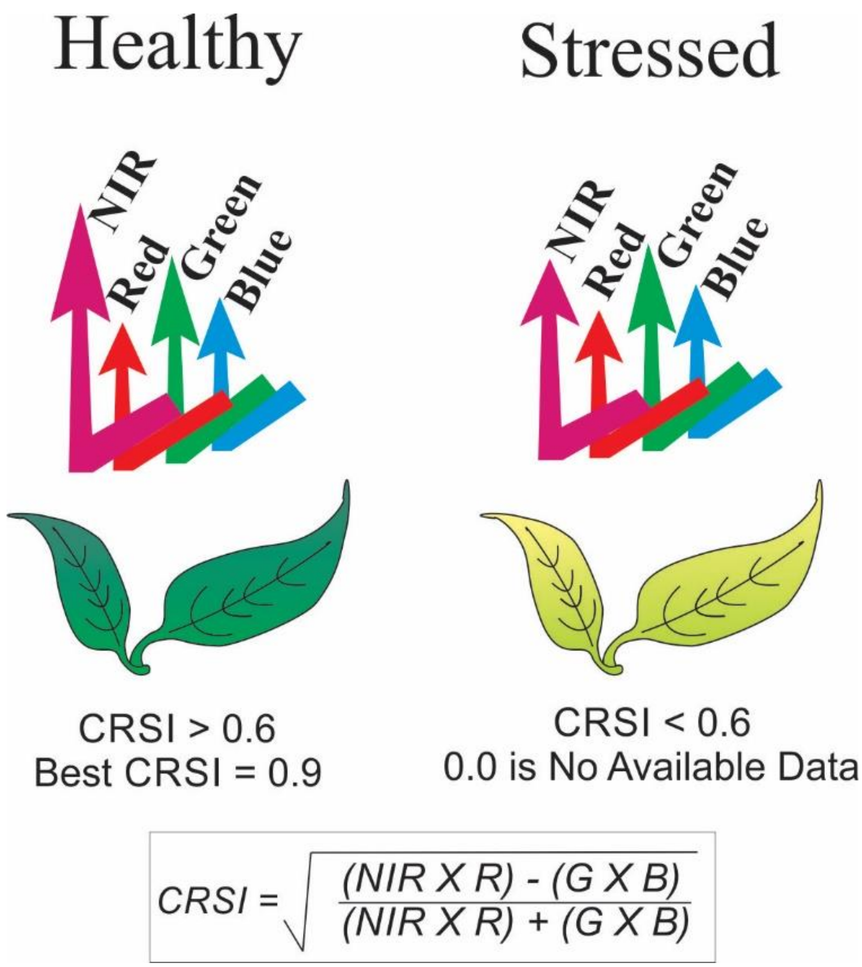

Figure 3.6: Graphical Representation of CRSI Values (Modified from Scudiero, Sakggs, and Corwin 2015).

CRSI calculations for respective bands are used for all Landsat images as per USGS band data information.

3.3.1 CRSI Band Analysis for Landsat 4,5 and 7 (Landsat TM, ETM+) Imagery

For Landsat 4, 5 and 7 (Landsat TM, ETM+) imagery, bands one, two and three are visible blue, green, and red bands, respectively, and band four is the NIR band. These four bands, a combination of the spectrum, are essential for vegetation, farmland, forestry, and ecology. Primarily, near infrared and red band combination determine the healthiness of the croplands by reflecting wavelengths to the sky. The CRSI equation for Landsat 4, 5 and 7 (Landsat TM, and ETM+) is given below:

$$\mathrm{CRSI}=\sqrt{\frac{(Band\ 4\times Band\ 3)-(Band2\times Band\ 1)}{(Band\ 4\times Band\ 3)+(Band2\times Band\ 1)}}$$

3.3.2 CRSI Band Spectrum Analysis for Landsat 8 (Landsat OLI, TIRS) Imagery

For Landsat 8, particularly band five measures the near infrared, or NIR and bands two, three and four are visible blue, green, and red respectively. CRSI Equation Formula for Landsat 8 (Landsat OLI) is given below.

$$\mathrm{CRSI}=\sqrt{\frac{(\mathrm{Band\ 5}\times\mathrm{Band\ 4})-(\mathrm{Band3}\times\mathrm{Band\ 2})}{(\mathrm{Band\ 5}\times\mathrm{Band\ 4})+(\mathrm{Band3}\times\mathrm{Band\ 2})}}$$

All Landsat 4, 5, 7, and 8 (Landsat TM, ETM+, and OLI) imagery scenes were collected from years 1982 to 2017 from the USGS Earth Explorer website (USGS, 2017). Geospatial statistics and image analysis of all Landsat imagery scenes conversion from DN (Digital Number) values to the respective RN (Reflectance Number) values were done using Environment for Visualizing Images (ENVI) 5.3 and Arc GIS 10.6 software.

Radiometric correction of all scenes, from DN value (Digital Number) to RN Values (Reflectance Numbers) was accomplished using a python code to account for sun angle and day of year (Courtesy: Mr. Morgan Burke, ESSP Department, University of North Dakota). This allowed for the procedure to be automate and simplify lengthy radiometric corrections in ENVI 5.3 software (L3Harris Geospatial, Broomfield, CO, USA). All radiometrically corrected, and georectified scenes were calculated using the proposed salinity index CRSI using Arc GIS 10.6 software. Known brine spill locations areas were mapped in ArcGIS (ESRI, Redlands, CA, USA), and the CRSI index was calculated in each the Landsat imagery. All scenes and images were kept 10% or less cloud cover and chosen from a farming season of June months to be maintained with consistency in time and month for better comparison results.

Palmer Drought Severity Index (PDSI) data was used to eliminate any drought-affected years to remove drought years from existing Landsat Data images to understand the error-free brine, and crude spills effect in the region post-, and pre-spills as drought impacts also show dryness and increased salinity levels in the land (Alley 1984; Alley 1985; NOAA 2018). Thus, all collected Landsat images were run through the proposed model builder (Figures 3.5 and 3.6) and compared for the CRSI year wise and date wise to understand pre- and post-salinity effect in the farmlands and vegetation.

3.4 The Palmer Drought Severity Index (PDSI)

PDSI uses temperature and precipitation data to determine drought affected zones by estimating relative dryness, which is a standardized index that spans in -10 (dry) + 10 (wet). PDSI is one of the most effective models to quantify long-term drought. In this particular model, temperature and precipitation data can predict drought effect through changes in evapotranspiration process (NOAA 2018).

3.4.1 Drought Impacted Years Eliminations as per PDSI Data

PDSI data were included as part of the research to minimize error in terms of determining the actual cause of lower CRSI values. Drought-affected vegetation and crops in the area may produce lower CRSI values. Thus, CRSI images with potential drought-affected years were removed to understand the significant difference over the period. The PDSI data related to the temperature and precipitation of the study area Bottineau County was obtained from NOAA, National Environmental Satellite Data, and Information Service (NOAA 2018). The drought months and years were downloaded in an Excel file from NOAA website. Bottineau county drought-affected years from June month were identified using computed methodology shown in as per the publication Alley (1984). The PDSI value ranges from 0 to -6, where negative values indicate the severity of drought condition, and positive values indicate wet conditions (Alley 1984).

Table 3.1: Palmer Drought Severity Index Dry Area Classification (Alley 1984).

PDSI Values	**Drought Severity of the Region**
0 to -0.5	Near Normal Climate
-0.5 to -1.0	Incipient Drought
-1.0 to -2.0	Mild Drought
-2.0 to -3.0	Moderate Drought
-3.0 to -4.0	Severe Drought
-4.0 to -6.0	Extreme Drought

Table 3.1 shows the dryness impacts on the region as per its PDSI values where PDSI values ranging from -2.5 and above in June month was chosen as draught parameters for this study. As per that PDSI values ranging above -2.5 to -6.0 in a dry climate comes under severe and extreme

drought conditions. As shown in Table 3.2, the drought-affected years in study area Bottineau County were determined as June months of 1988 and 1989 for this project as cut off PDSI -2.5 and above data.

Table 3.2: Most Drought Affected Years in Bottineau County.

Year	Month	PDSI
1987	6	-2.42
1988	6	-5.44
1989	6	-2.76
1991	6	-2.45
1992	6	-2.24
2008	6	-2.36
2017	6	-2.25

3.5 The Arc GIS Model Builders for Landsat 4, 5, 7 and 8 (Landsat TM, ETM+, OLI)

Figures 3.7 and 3.8 show the Arc GIS Models workflows primary used in this research to achieve the CRSI Values.

3.5.1 The ArcGIS Model for Landsat 4,5 and 7 (Landsat TM, ETM+)

The Figure 3.7 shows the Arc GIS Model for Landsat 4,5,7 (Landsat TM, ETM+) where the full or more than half covered, geometrically and radiometrically corrected Bottineau County study area Landsat imagery individual bands blue (band 1), green (band 2), red (band 3), and near-infrared (band 4) were run through equation 7. CRSI formula calculated Bottineau County imagery was clipped into the desired study area, and this process was done through the batch for all Landsat 4, 5, and 7 imagery (Figure 3.7).

3.5.2 The ArcGIS Model for Landsat 8 (Landsat OLI)

Figure 3.8 shows the simplified used ArcGIS (ESRI, Redlands, CA, USA) geoprocessing model for Landsat 8 (Landsat OLI). In this procedure also as stated above the full or more than half covered, geometrically and radiometrically corrected Bottineau County study area Landsat imageries individual bands blue (band 2), green (band 3), red (band 4), and near-infrared (band5) were run through equation 8. The CRSI calculated imageries were clipped as per desired study area and processed was followed batch-wise to achieve the desired results (Figure 3.8).

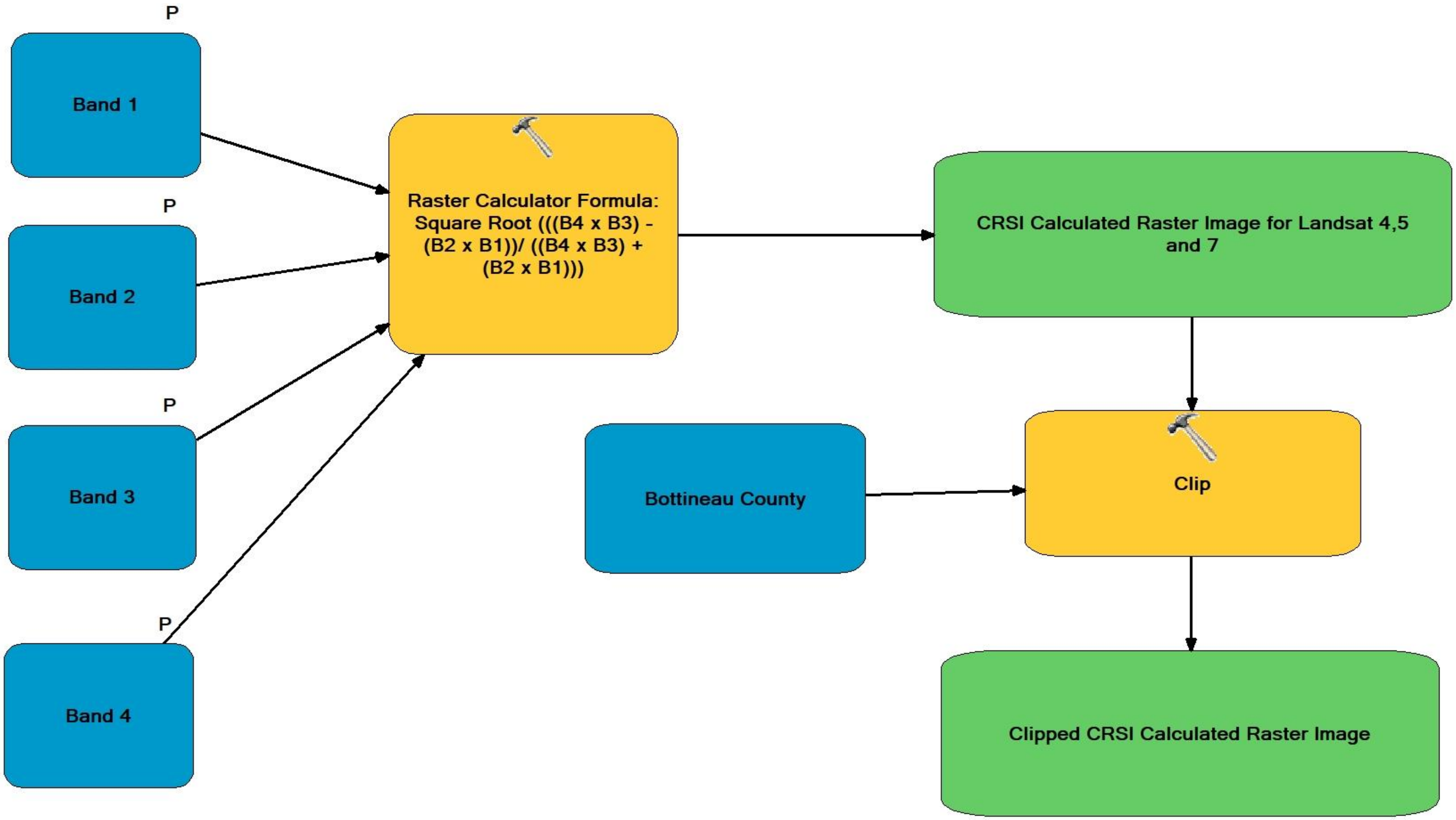

Figure 3.7: The ArcGIS Model Builder for Landsat 4, 5 and 7 (Landsat TM, ETM+)

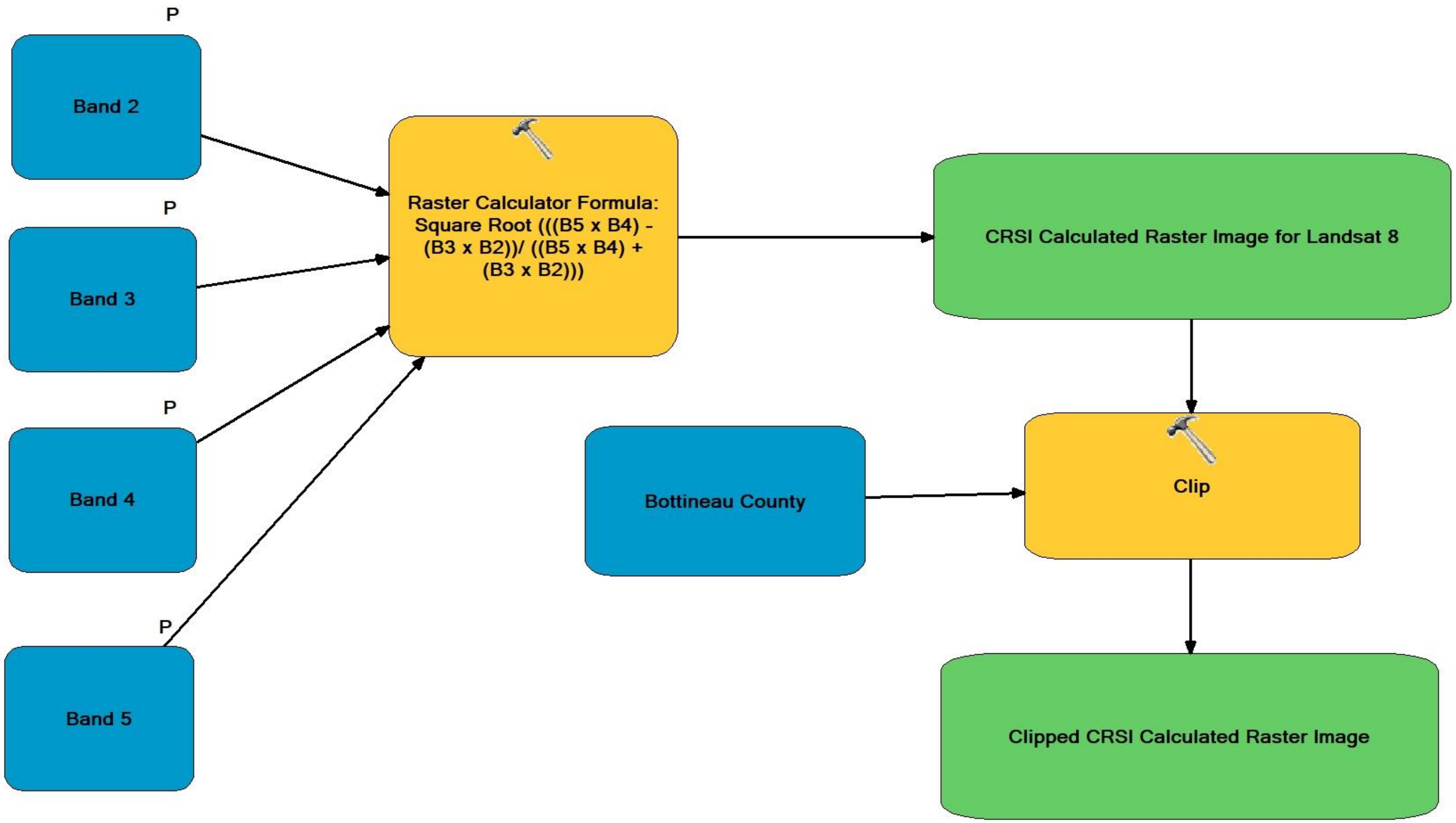

Figure 3.8: The Arc GIS Model Builder for Landsat 8 (Landsat OLI)

3.6 Statistical Analysis of CRSI Values of All Location IDs of Landsat Images

Statistical data analyses were conducted using Excel Data Analyzer (Microsoft Office 10, Seattle, Washington) and XLSTAT (ADINSOFT Inc., Long Island City, New York). Summary statistics and least squares regression analysis were conducted in Excel. Mann-Kendall, Kendall's tau, and Theil-Sen analysis were conducted in XLSTAT.

3.6.1 Mann-Kendall Analysis

The Mann-Kendall test or M-K test is a non-parametric test used for the data analysis of time-based series where the trend of time is featured in Y-axis values in either decreasing or increasing form, which means the test works for all distribution with no serial correlation (Manly 2008). This method is often used to analyze water quality data. It was used in this case to assess the changes in CRSI values over time for known brine spill locations. In short, Mann-Kendall trend tests analyze the changes in time between the initial time and later time where all data points are compared with the previous data. This research study has used this model mainly to understand the time-based analysis of the nonparametric data to understand the trend with the median 50th percentile Sen's slope. The test is useful to understand the upward or downward trend over the period time, which may be linear or nonlinear nonparametric data (Manly 2008)

$$n \times (n-1)/2,$$

Where n = no of observations

The Mann-Kendall data results have a null hypothesis and alternate hypothesis where the null hypothesis (h0) means no monochromatic trend while in alternate hypothesis (ha) trend exist which can be positive or negative or not-null.

3.6.1.1 Kendall' tau

Kendall's tau is a non-parametric correlation coefficient which is measured statistically to understand the strength of two variables association and relationship

$$\tau = \frac{(\text{number of concordant pairs}) - (\text{number of discordant pairs})}{n(n-1)/2}.$$

Concordant means the variables with the same direction, while they may not be the same rank (both 1st and both 2nd), each variable is ordered equally higher or equally lower. The discordant means the variable are not in the same directions and the one variable may contain higher values than another variable. Thus Concordant pairs and discordant pairs refer to comparing two pairs of data points to see if they "match." Concordant pairs and discordant pairs are used in the following Kendall's Tau equation.

3.6.1.2 Kendall's P-value

The p-value associated with the Mann-Kendall test or M-K Test is the most critical concept of statistical significance. The applicability of the results of a trend test shows that if P-value < 0.05 means monotonic trend and if τ is +ve, increasing trend, and if τ is -ve, decreasing trend. The P value >0.05 means from a monotonic trend. The p-value represents the probability of an error when the real value of the parameter varies from the calculated data. Usually, if the p-value is under 0.05 suggests the alternative hypothesis, because the risk of its invalidity is relatively low in comparative data (Manly et al. 2008).

3.6.1.3 Theil-Sen Trend Lines (Sen's Slope, Nonparametric Method to Test Trends)

The Theil-Sen line is a nonparametric alternative test. A Theil-Sen line is a fitting line to observation points in the plane by selecting the median (50th percentile) of the slope which changes linearly with time. This method is widely used statistically and proven more accurate than the simple regression and least squared methods. The method is widely used in nonparametric analysis instead of parametric skewed and heteroskedastic statistical analysis. (Manly et al. 2008).

3.6.2 Linear Regression Analysis, Root Mean Square and P-Values Significance

The least squares regression line models show the mean values concentration changes linearly with time. Regression analysis and p-values combined in a relationship show that the model is statistically significant or not significant in terms of a parametric relationship. The coefficients show the mathematical association between each dependent and independent variables. The p-values of coefficients indicate the statistical significance of the data. Least squares regression models show variations in the model where the higher R^2 value shows the better-fitted in terms of the significance of the model. For example, 0.2 R^2 values mean that the model explains 20% variations in the given data. Four possible scenarios can be derived from the regression analysis, R^2 values, and P- Values, which can determine the significance of the model (Manly et al. 2008).

1. Low R-squared and low P-values (P-value <= 0.05) means not much variation in the data, but p values are significant (Model exist on one parameter only which is ok but not so perfect).
2. Low R-squared and high P-values (P-value > 0.05) means model does not have much variations and data has no significance (Worst no fitting type model with no significance)
3. High R-Squared and low P-values mean lots of variations and data has significance values (Best fitted model)
4. High R-squared and high P-values mean the model has lots of variations, but the data has no significance (Model of no use).

Chapter 4
Results and Discussion

4.1 Brine Spills Visual Inspection

Twelve brine impacted sites of farmland adjacent to oil wells, injection wells facilities were visited on September 16, 2016, by Neha Patel, Brad Rundquist and Greg Vandeberg of the University of North Dakota. The team met with local landowners Daryl and Christine Peterson, reporter Austin Schauer and brine spills advocate Fintan Dooley. The sites were inspected, and impacts were observed and documented.Longitude and latitude coordinates were recorded at the contaminated sites using a Garmin GPSMap64 (Olathe, Kansas) (Table 4.1).

Table 4.1: List of Visited Sites Coordinates, Bottineau County.

Site ID	Latitude	Longitude	Elevation	Visitation Date
1	48.79	-101.48	524.17	9/16/2016
2	48.81	-101.47	502.82	9/16/2016
3	48.80	-101.34	482.46	9/16/2016
4	48.80	-101.34	480.06	9/16/2016
5	48.78	-101.31	467.78	9/16/2016
6	48.75	-101.25	458.28	9/16/2016
7	48.74	-101.23	464.60	9/16/2016
8	48.74	-101.20	457.93	9/16/2016
9	48.74	-101.21	460.95	9/16/2016
10	48.81	-101.20	459.58	9/16/2016
11	48.82	-101.21	461.26	9/16/2016
12	48.82	-101.21	460.75	9/16/2016

Many of the sites had limited or no vegetation growth (Fig. 4.1-4.2). The research team was informed that the well operators and farm owners had worked towards the reclamation (primarily soil removal) of some of the locations with limited success.

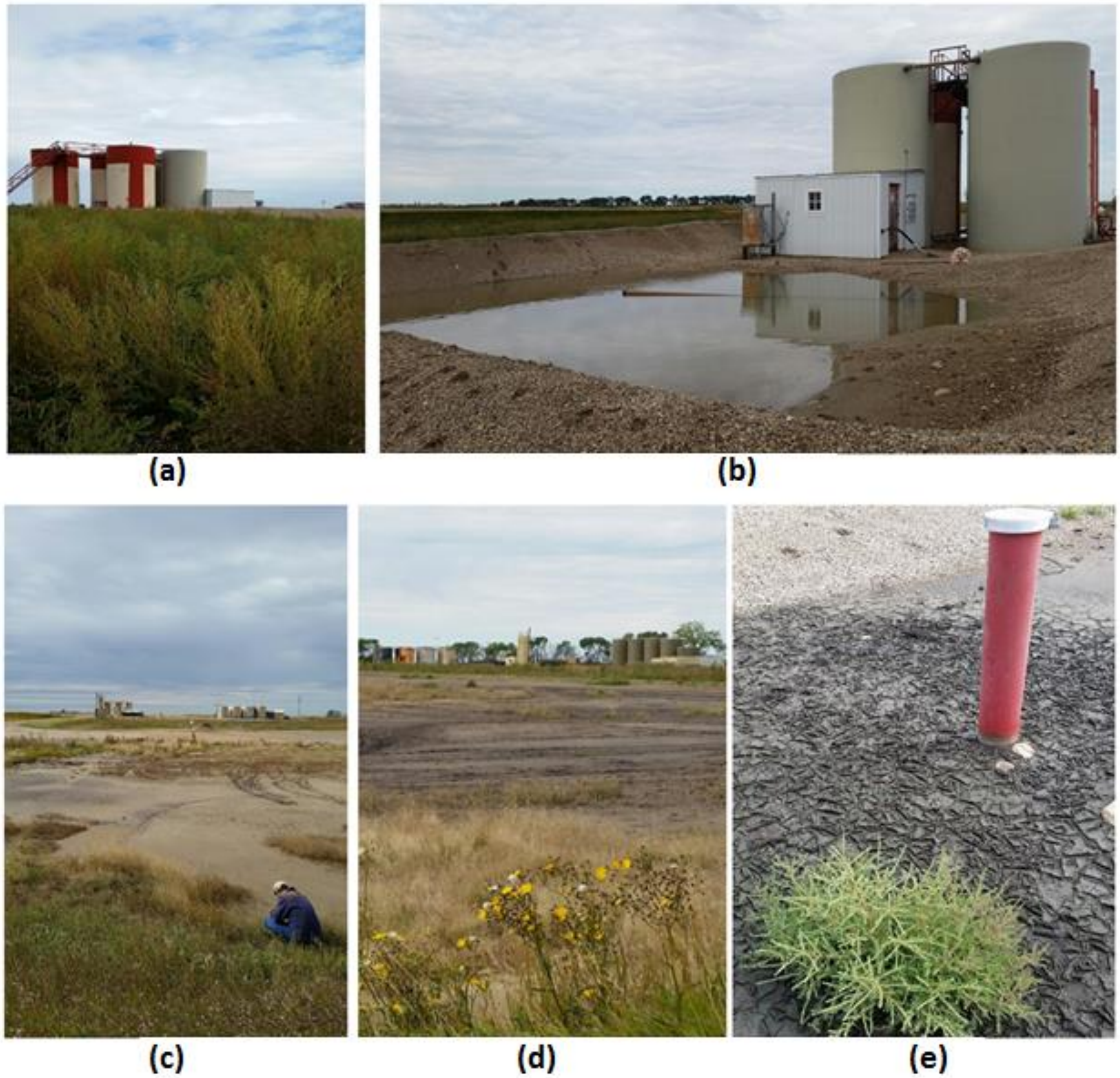

Figure 4.1: Photographs showing (a) an oil pumping and storage site, (b) a brine spill near the location (c), (d) bare and scalded farmland, and (e) salt tolerant plant growth. Source: Neha Patel (9/16/2016).

Figure 4.2: Brine Spill Site near Bottineau, ND, Source: Neha Patel (9/16/2016).

4.2 Reporting of Brine Spills

North Dakota has under-reported, or not reported salt spills because of its leniency in brine spills reporting regulation (EERC 2015; Springer 2018). Most oil production facilities in other states are required to report oil and brine spills report for one barrel onwards; while North Dakota has brine and crude spills reporting is 1,589.87 liters (10 barrels or 420 gallons) onwards for "contained" spills (Figures 4.1, 4.2, 4.3; EERC 2015; Springer 2018). State lawmakers have agreed to look at this matter seriously to make reporting of one barrel oil and crude spills as a requirement. Also, since many of these spills are not reported, the exact total estimate is not available (Springer 2018).

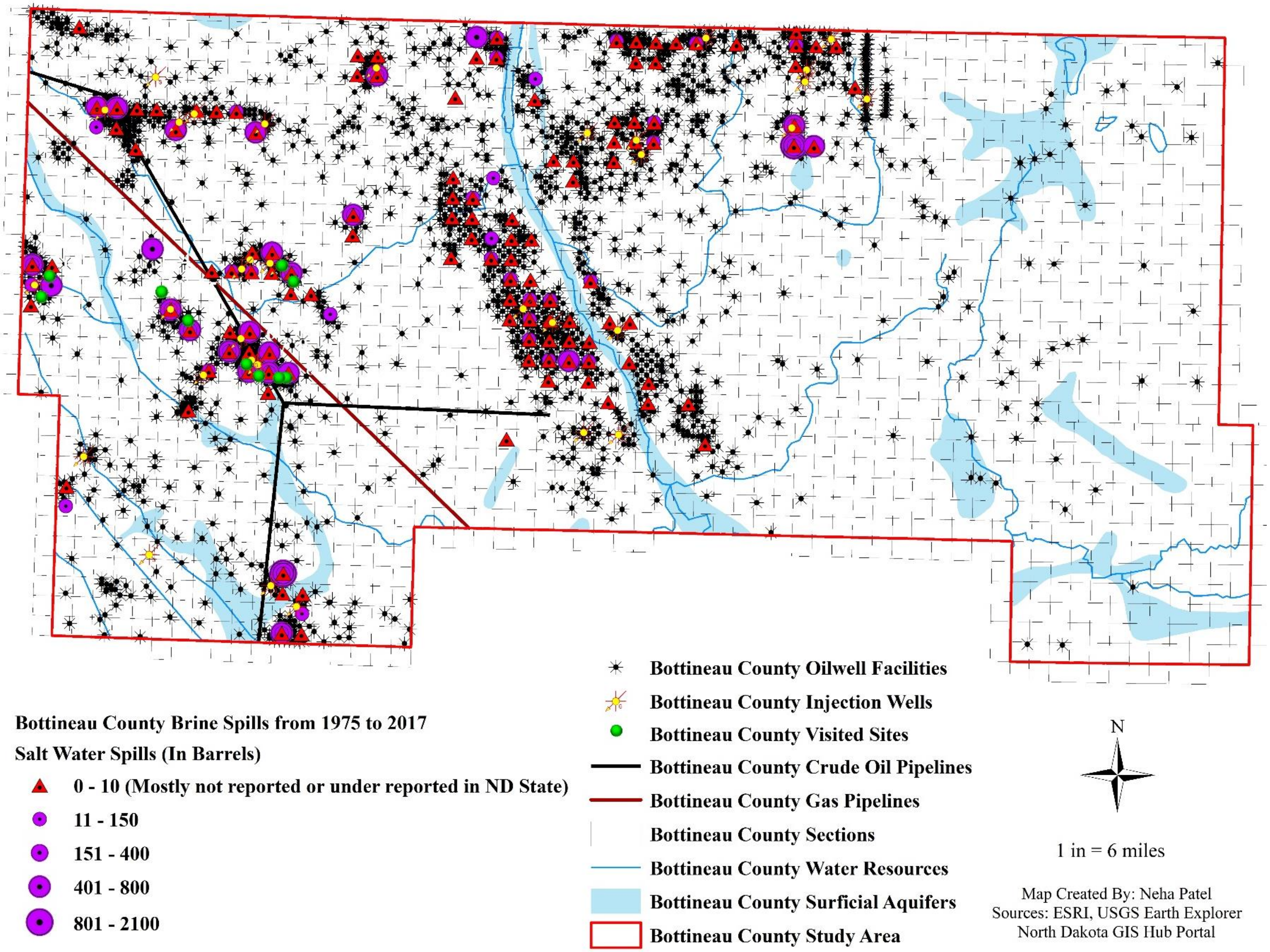

Figure 4.3: Bottineau County Brine Spills from Years 1975 to 2017.

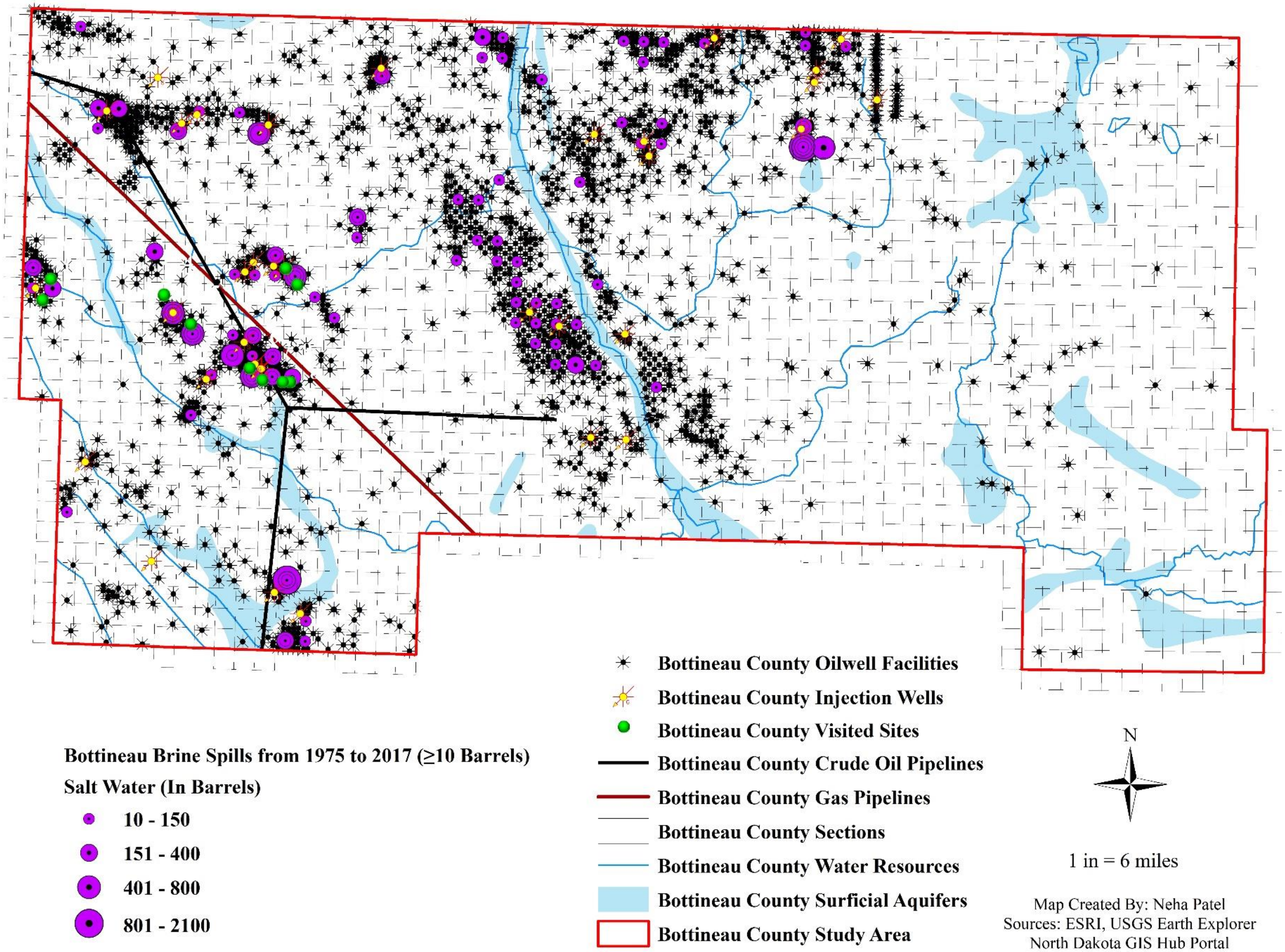

Figure 4.4: Bottineau County Brine Spills from Years 1975 to 2017 (≥ 10 Barrels)

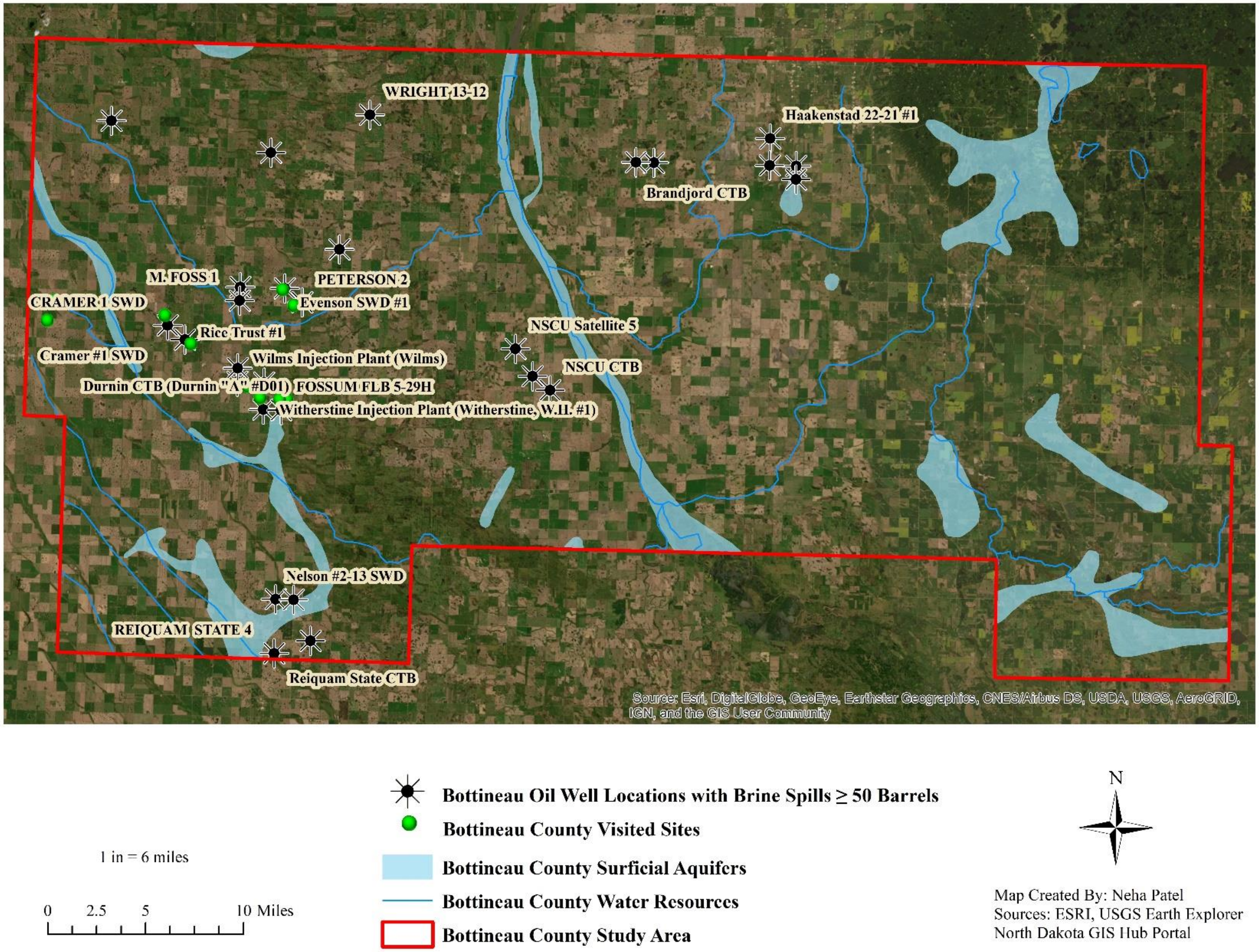

Figure 4.5: Bottineau County Oil Well Locations with Brine Spills ≥ 50 Barrels from Years 1975 to 2017.

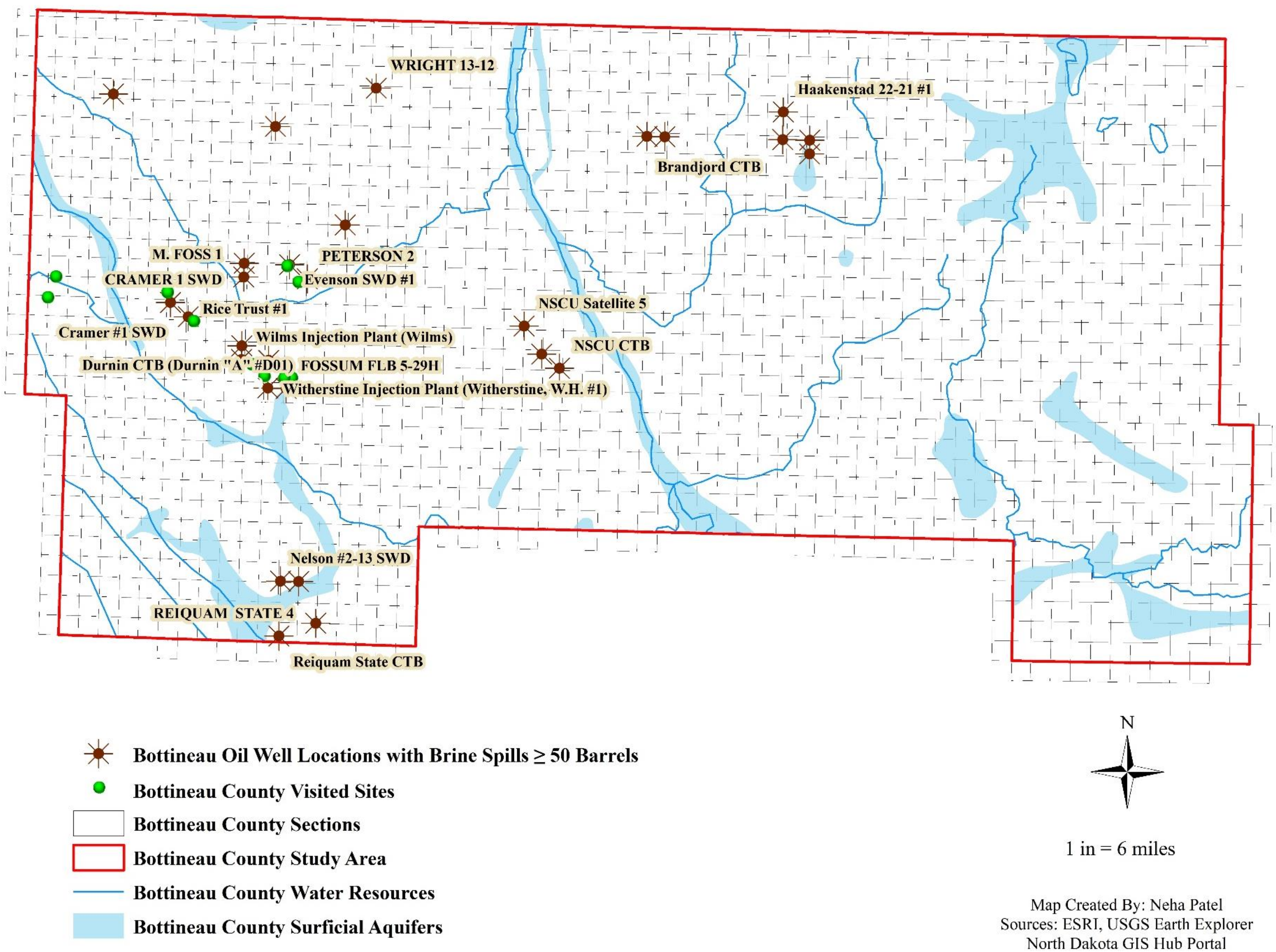

Figure 4.6: Bottineau County Sectionwise Oil Well Locations with Brine Spills ≥ 50 Barrels from Years 1975 to 2017.

4.3 Brine Spills Statistics

Bottineau County had a total of 575 brine and crude spills reported between the years 1975 and 2017 (Tables 4.2-4.4). In terms of brine spills, the area had a maximum of 0.33 million liters (2,100 barrels) with a total sum of 3.8 million liters (23,912 Barrels), the mean value of 6612.3 liters (41.6 barrels) and the Standard Deviation value of 22719.3 liters (142.9 barrels). Also, the crude spills with a maximum of 63,594.9 liters (400 barrels) and the total sum of 0.9 million barrels (5,660.9 barrels), mean 1,564.4 liters (9.8 barrels) and standard deviation of 4,780.8 liters (30.1 barrels) values (Tables 4.2, 4.3). In addition to that " Other Volume″ analysis including fracking fluid and mud, fluid is also shown in the table with 0.16 million liters (1,000 barrels) maximum, 0.38 million liters (2,378 barrels) of sum, mean 651.9 liters (4.1barrels) and standard deviation of 7,440.6 liters (46.8 barrels) (Table 4.4). Also, histograms for brine as well as crude spills years wise show the analysis of spillage in detail (NDDH 2017).

Table 4.2: Brine Spills Statistics: Bottineau County from years 1975-2017.

	Liters	Barrels
Counts	575.0	575.0
Minimum	0.0	0.0
Maximum	0.33 million	2100.0
Sum:	3.8 millions	23911.9
Mean	6611.6	41.6
Standard Deviation	22719.0	142.9
Nulls	0.0	0.0

Table 4.3: Crude Oil Spills Statistics: Bottineau County 1975-2017.

	Liters	**Barrels**
Counts	575.0	575.0
Minimum	0.0	0.0
Maximum	0.064 million	400.0
Sum	0.09 million	5660.9
Mean	1565.2	9.8
Standard Deviation	4781.4	30.1
Nulls	0.0	0.0

Table 4.4: "Other Liquid" Volume Statistics 1975-2017.

	Liters	**Barrels**
Counts	575.0	575.0
Minimum	0.0	0.0
Maximum	0.15 million	1000.0
Sum	0.38 millions	2378.0
Mean	657.5	4.1
Standard Deviation	7447.5	46.8
Nulls	0.0	0.0

4.3.1 Timing of Brine and Crude Oil Spills from Years 1975-2017

As per the graphical analysis is shown in Figure 4.7, 4.8, 4.9, 4.10 in Bottineau County, the highest brine spills are noted at 0.33 million liters (2,100 barrels) on Sept. 20, 2004, followed by 0.24, 0.13, 0.11, 0.10, 0.09 million liters (1,500, 800, 700, 650, 600 barrels) on July/21, 2011, June 26, 2012, June 6, 2014, Nov. 19, 2011, Jan. 6, 2004, and Oct. 26, 2012 respectively (Figures 4.7, 4.9; Table 4.2).

The highest crude oil spills in the Bottineau County region are noted at 0.06 million liters (400 barrels) on Oct. 19, 1976 followed by 0.04, 0.03, 0.028, 0.025, 0.024, 0.023 million liters (260,200,175,160,155,150 barrels) on Jan. 7, 2015, June 1,1994, March 13, 2008, March 9, 1976, Aug. 7, 2001 and Feb. 17,1976 respectively (Table 4.3, Figures 4.8, 4.10). All reported crude spills have a sum of 0.89 million liters (5655 barrels), with a maximum 0.06 million liters (400 barrels) and a minimum of 0 to 159 liters (0 to 1 barrel) between years 1975 to 2017. Approximately 78 incident IDs out of 575 total data had no clear-cut crude spills information with "blank" data. As per Incident ID report, out of 576 total brine and crude spills reports, 224 consists of crude spills report (NDDH 2017).

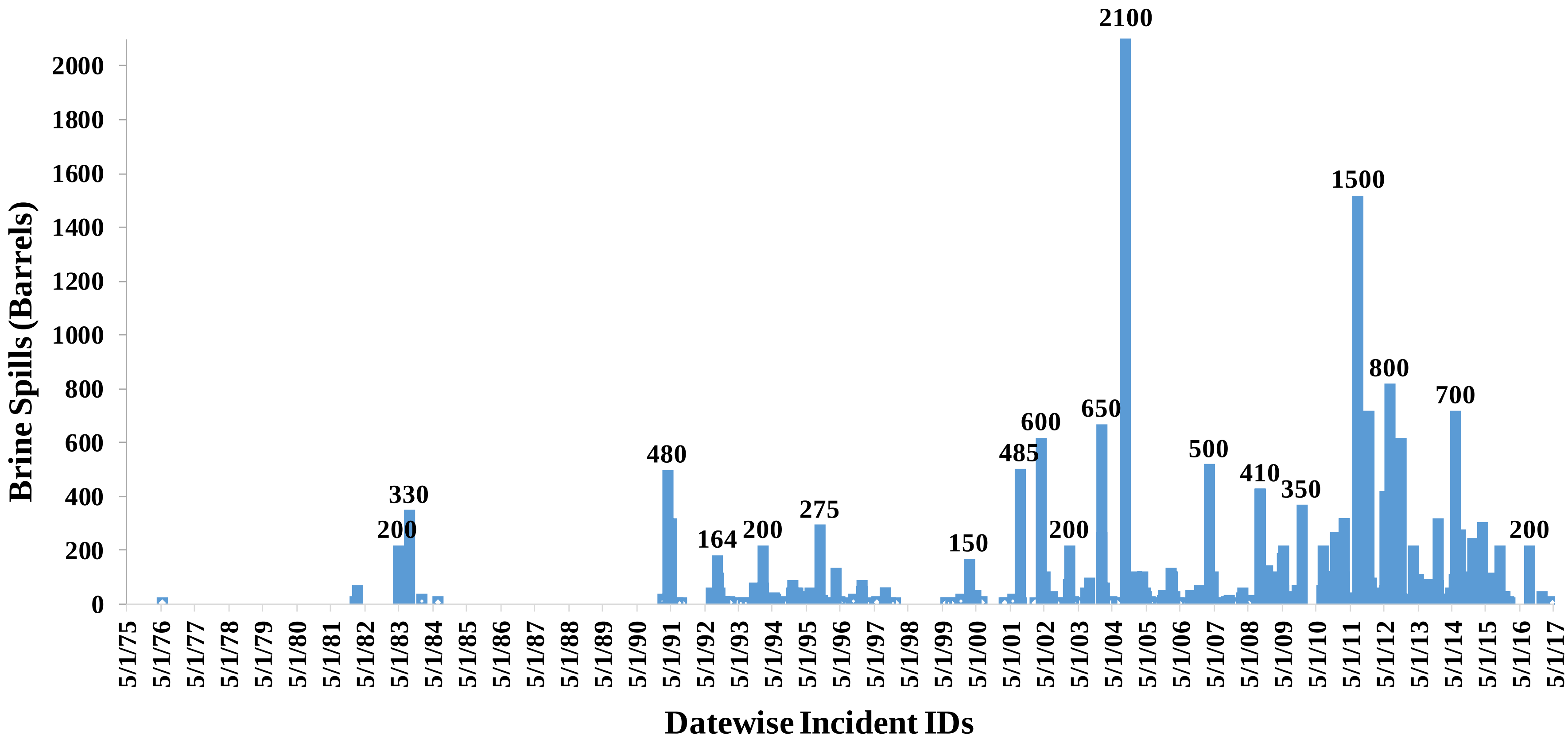

Figure 4.7: Bottineau County Brine Spills Datewise from Years 1975-2017.

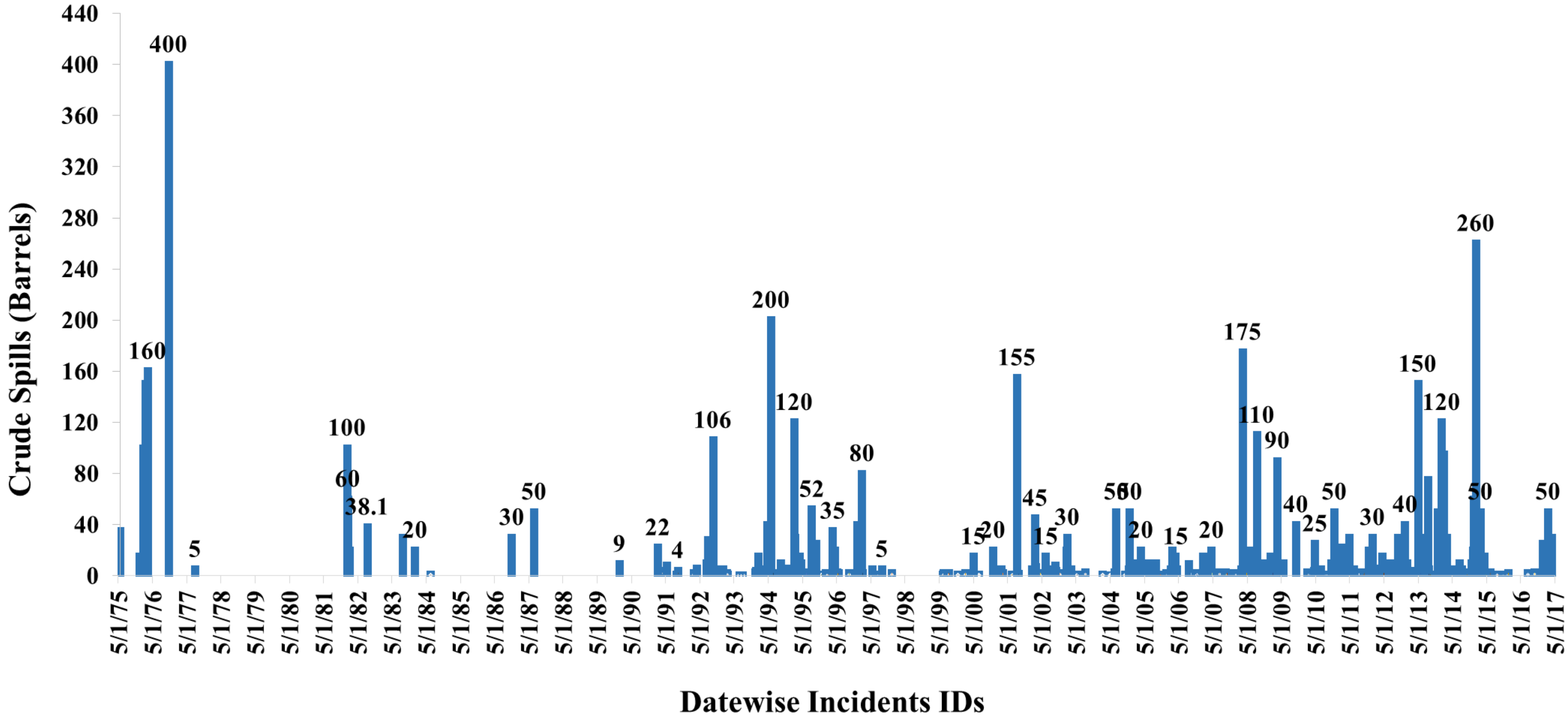

Figure 4.8: Bottineau County Datewise Crude Spills from Years 1975-2017.

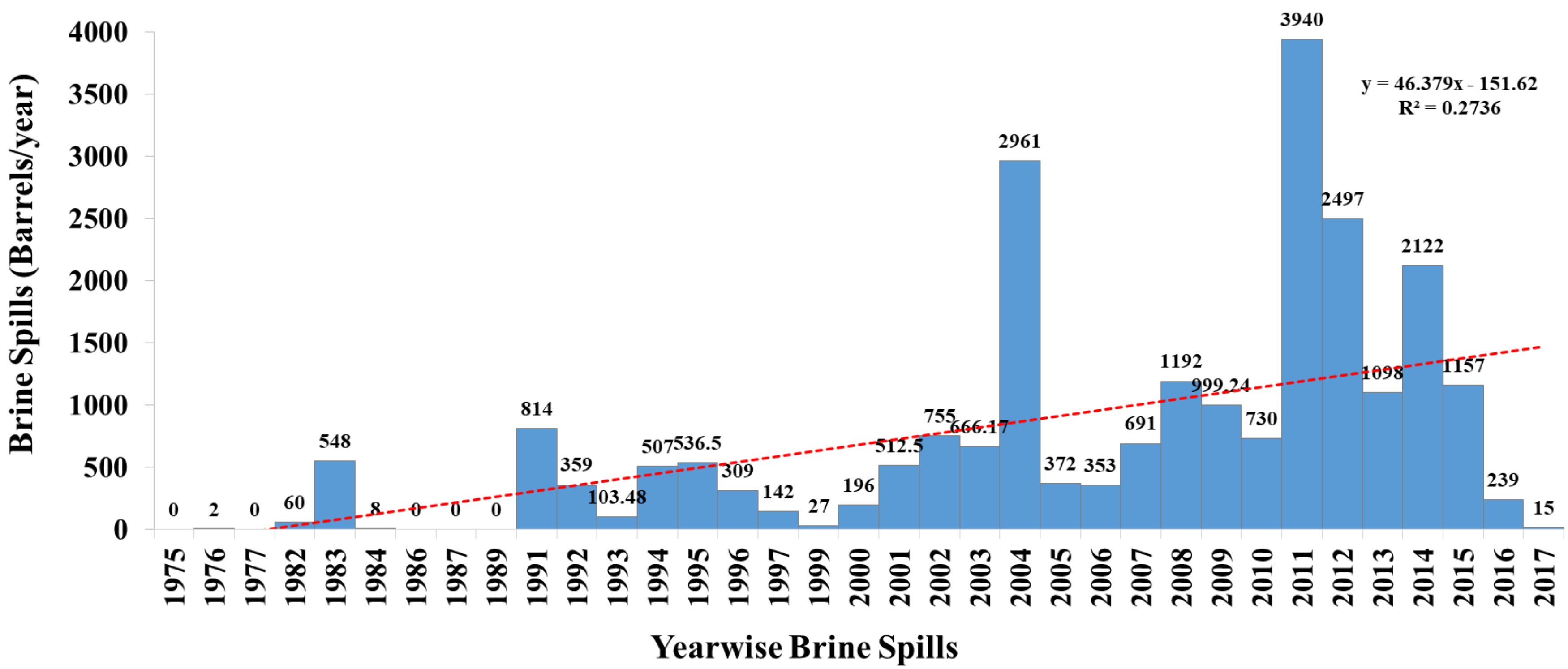

Figure 4.9: Bottineau County Brine Spills Yearwise from Years 1975-2017.

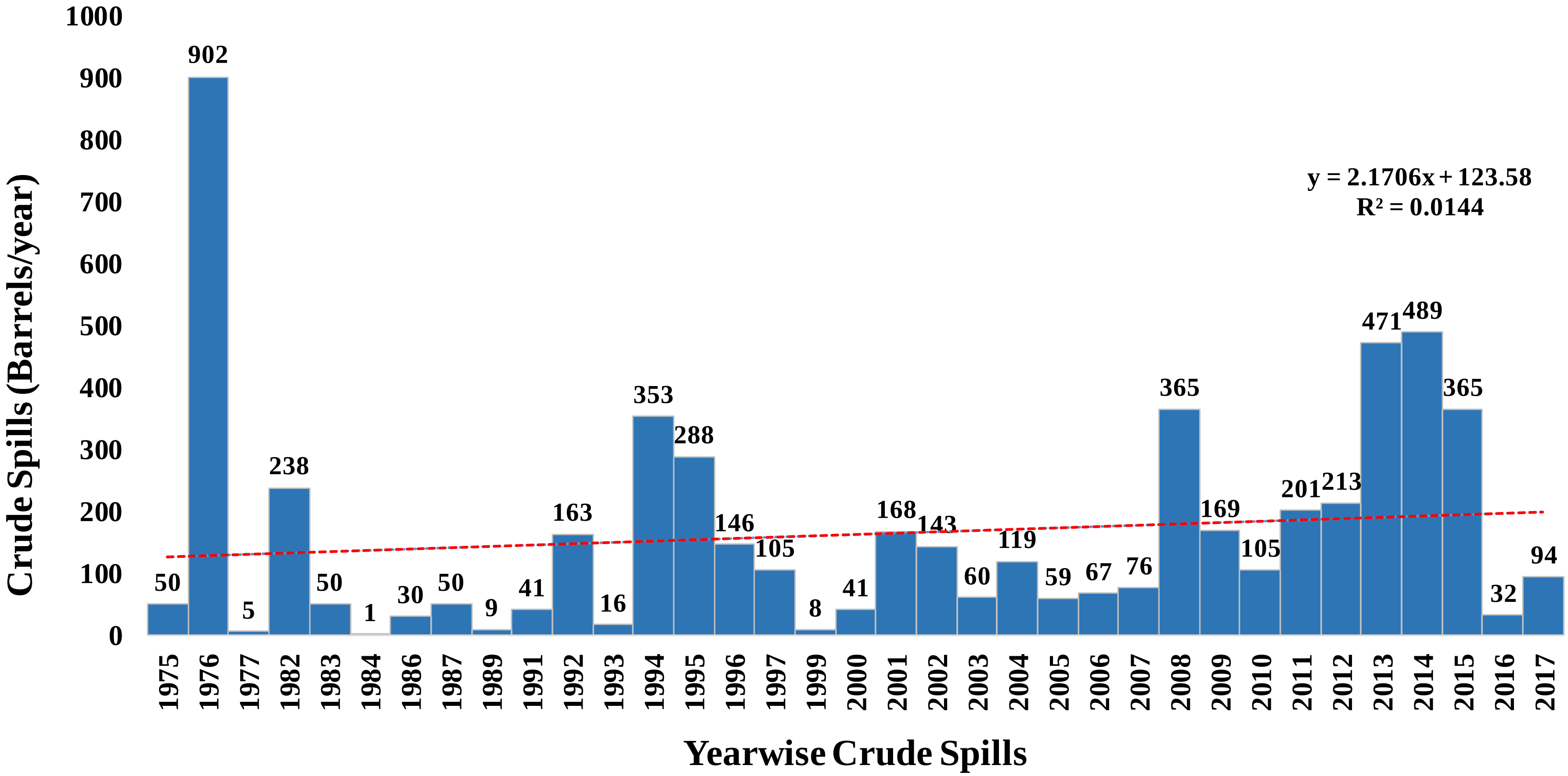

Figure 4.10: Bottineau County Crude Spills Yearwise from Years 1972 to 2017.

4.4 CRSI Calculated Images of Study Area, Bottineau County (1986 to 2017)

A total of 24 Landsat Images were collected from Landsat 4, 5, 7 and 8 from 1982 to 2017 for the month of June. The first precise visible image date starts from 1986 June month for this study since previous years' images from June 1982 to 1985 had more than 50% cloud cover in some cases without clarity. The CRSI salinity index was performed on radiometrically corrected images. The results of the images are shown in Figures 4.11 to 4.19 and Appendix A. All images use the same color legend to keep uniformity in results; wherein classification "0" CRSI value means "no Data," "0.0 to 0.6" CRSI values are shown as "unhealthy" vegetation zones. CRSI values between "0.6 to 0.7", "0.7 to 0.8" and "0.8 to 1.0" are shown as "moderately healthy," " healthy" and "excellently healthy" vegetation areas zones for farmland. These images were downloaded in Landsat tiles format from the USGS Earth Explorer website, so three of the images respectively from June 1995, June 2009 and June 2010 only cover part of the study area. The rest of the 21 images are fully clipped with the Bottineau County area sections showing ≤ 10 % clouds. In these images, bright red areas near cropland show low CRSI values to highlight the potential impact of brine spills or seepages near croplands and vegetation (Fig. 4.11-4.19, Appendix A). The brine spills along with Bottineau county primary hydro resources and aquifers also shown in all images for proper area visualization. Also, images of years 1988, 1989, 2006, 2017 and 2018 (Appendix A) have a large patch of red which is part of ≤ 10% clouds which is considered as no data or error.

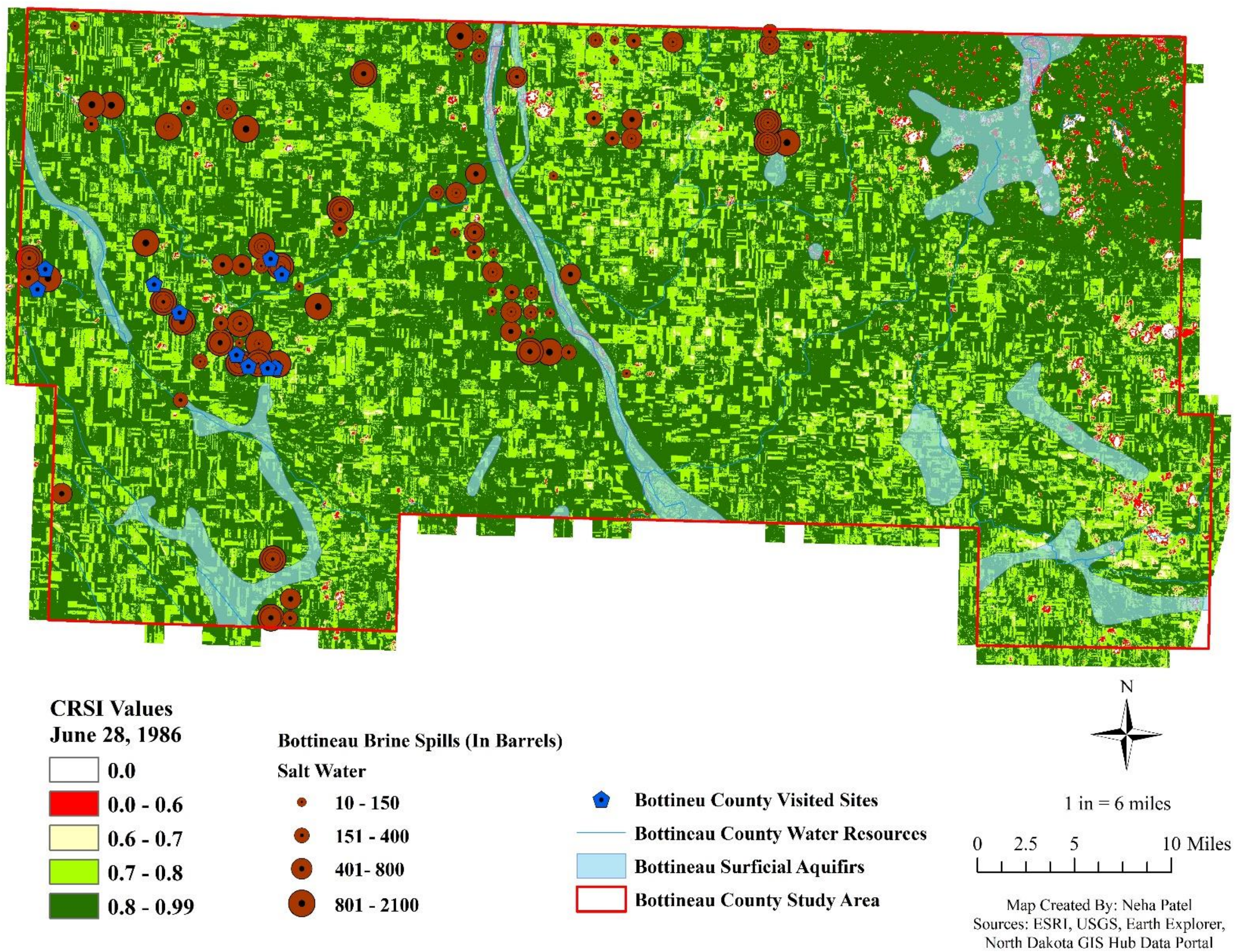

Figure 4.11: Bottineau County CRSI Values (with brine spill shown for reference) on June 28, 1986.

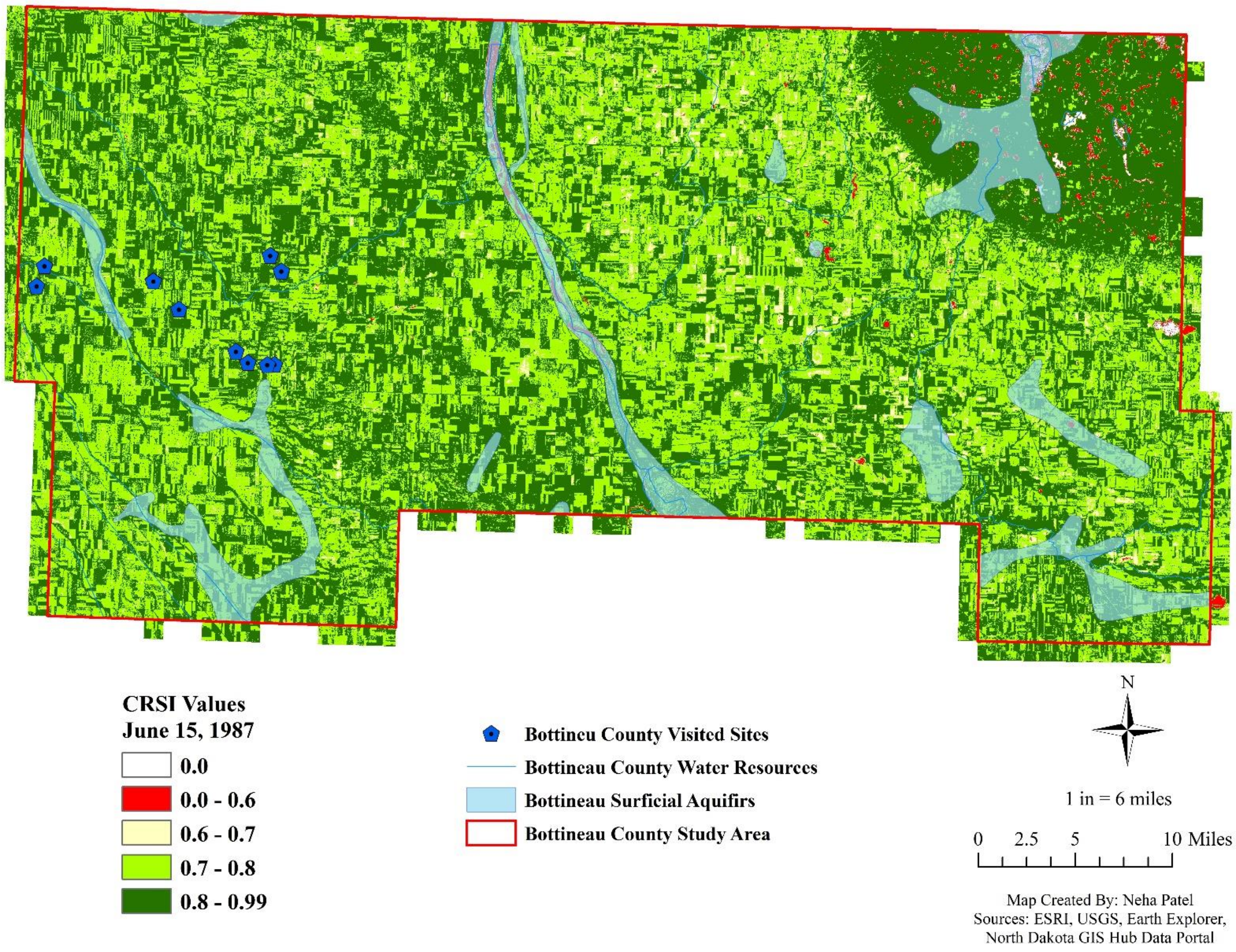

Figure 4.12: Bottineau County CRSI Values on June 15, 1987.

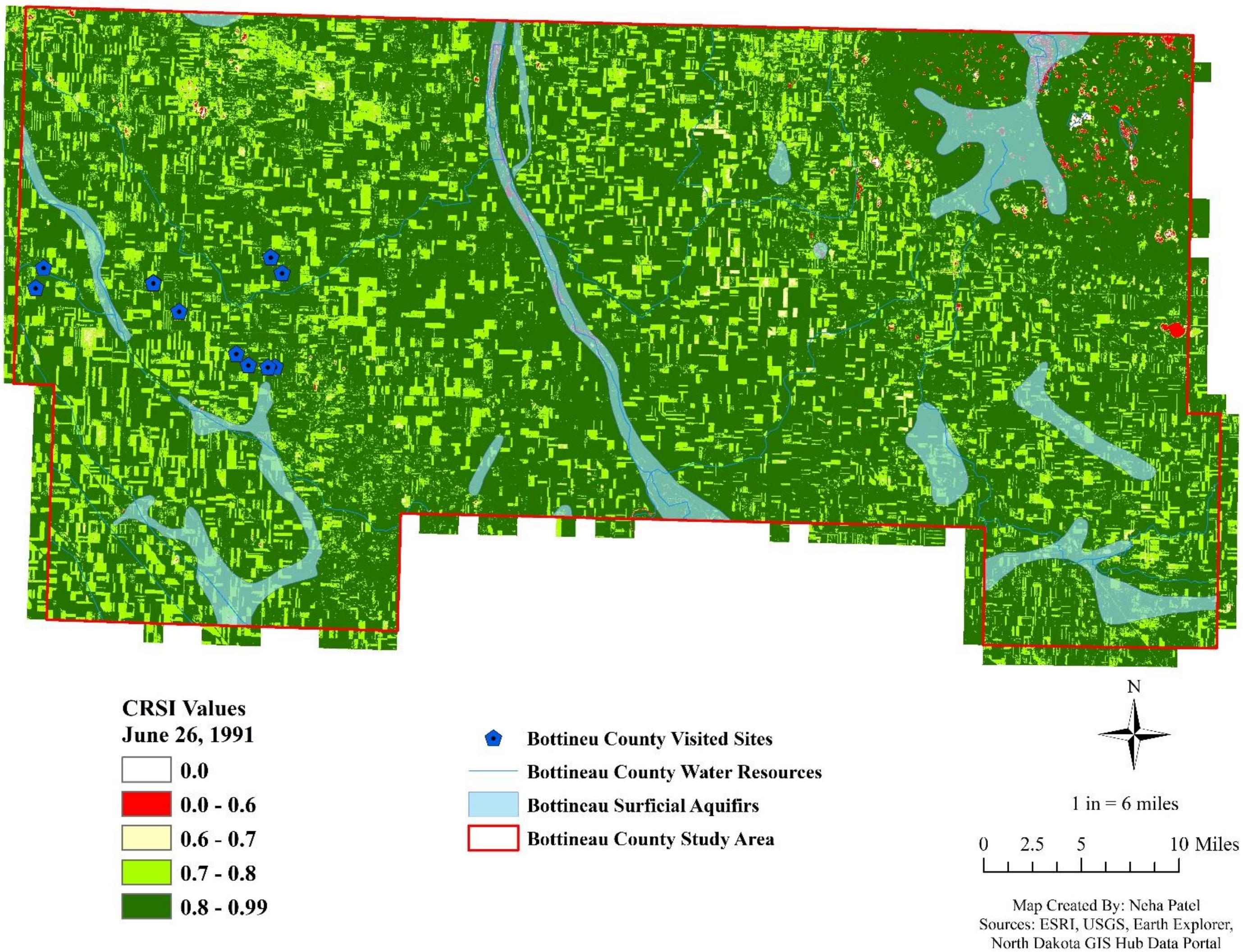

Figure 4.13: Bottineau County CRSI Values on June 26, 1991.

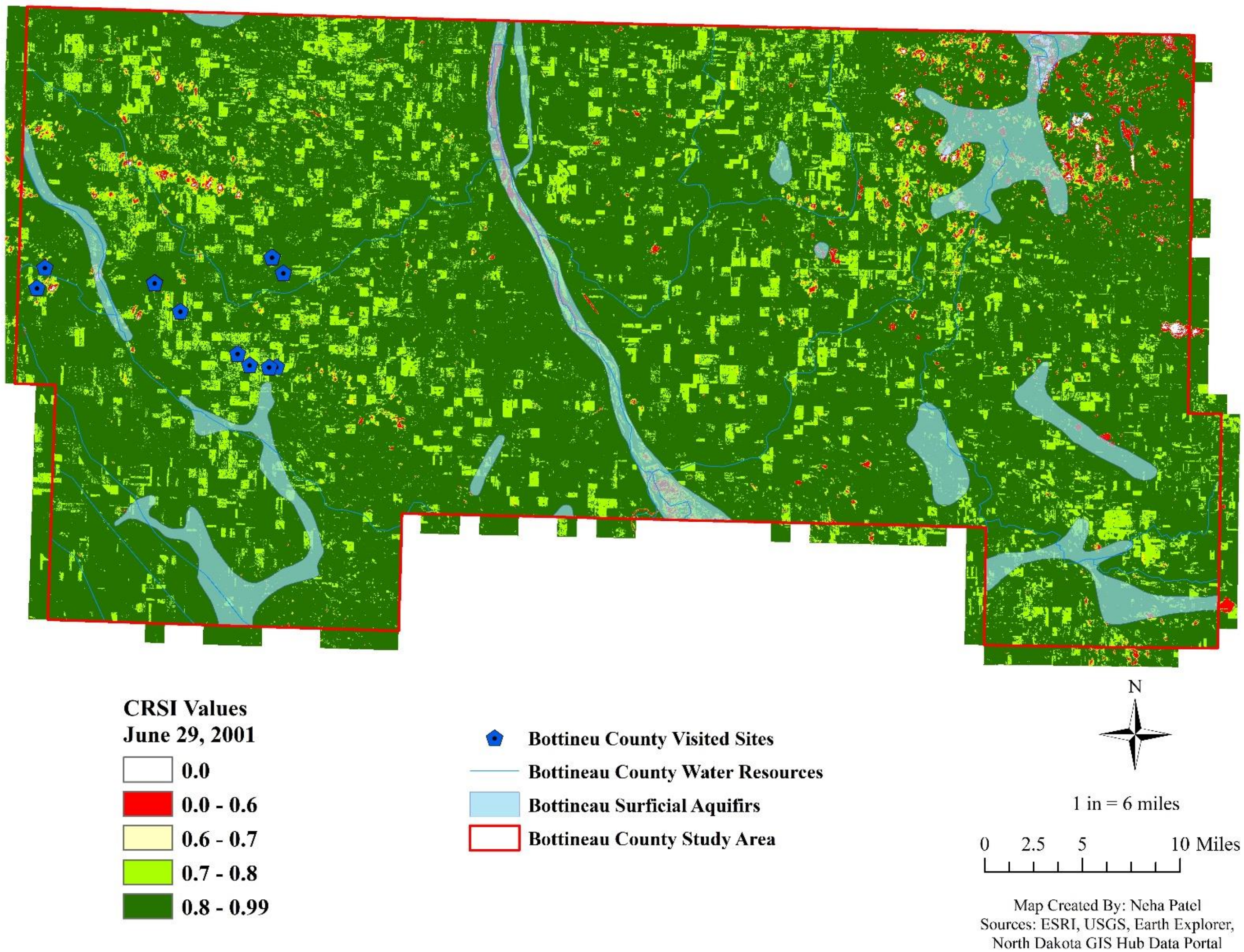

Figure 4.14: Bottineau County CRSI Values on June 29, 2001.

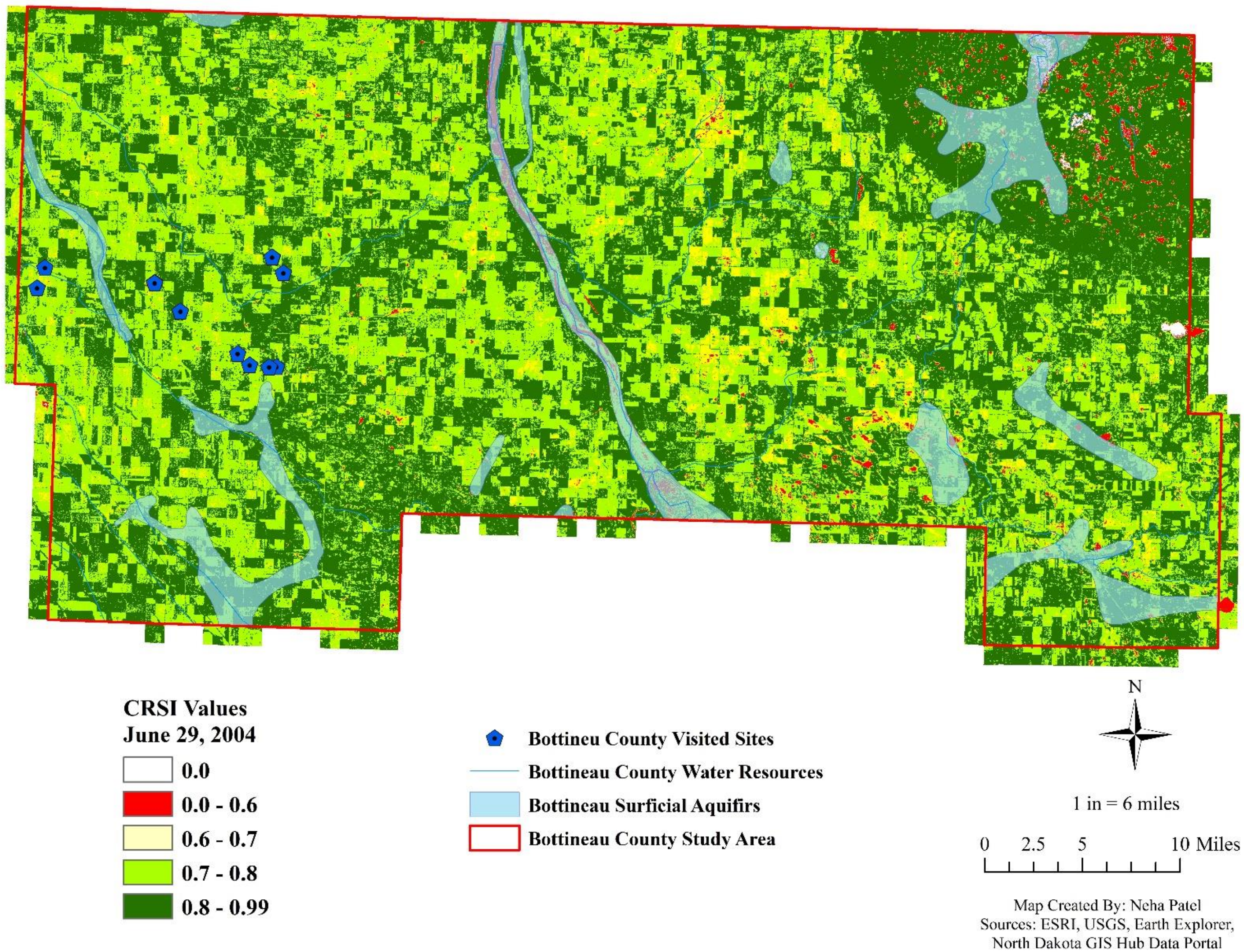

Figure 4.15: Bottineau County CRSI Values on June 29, 2004.

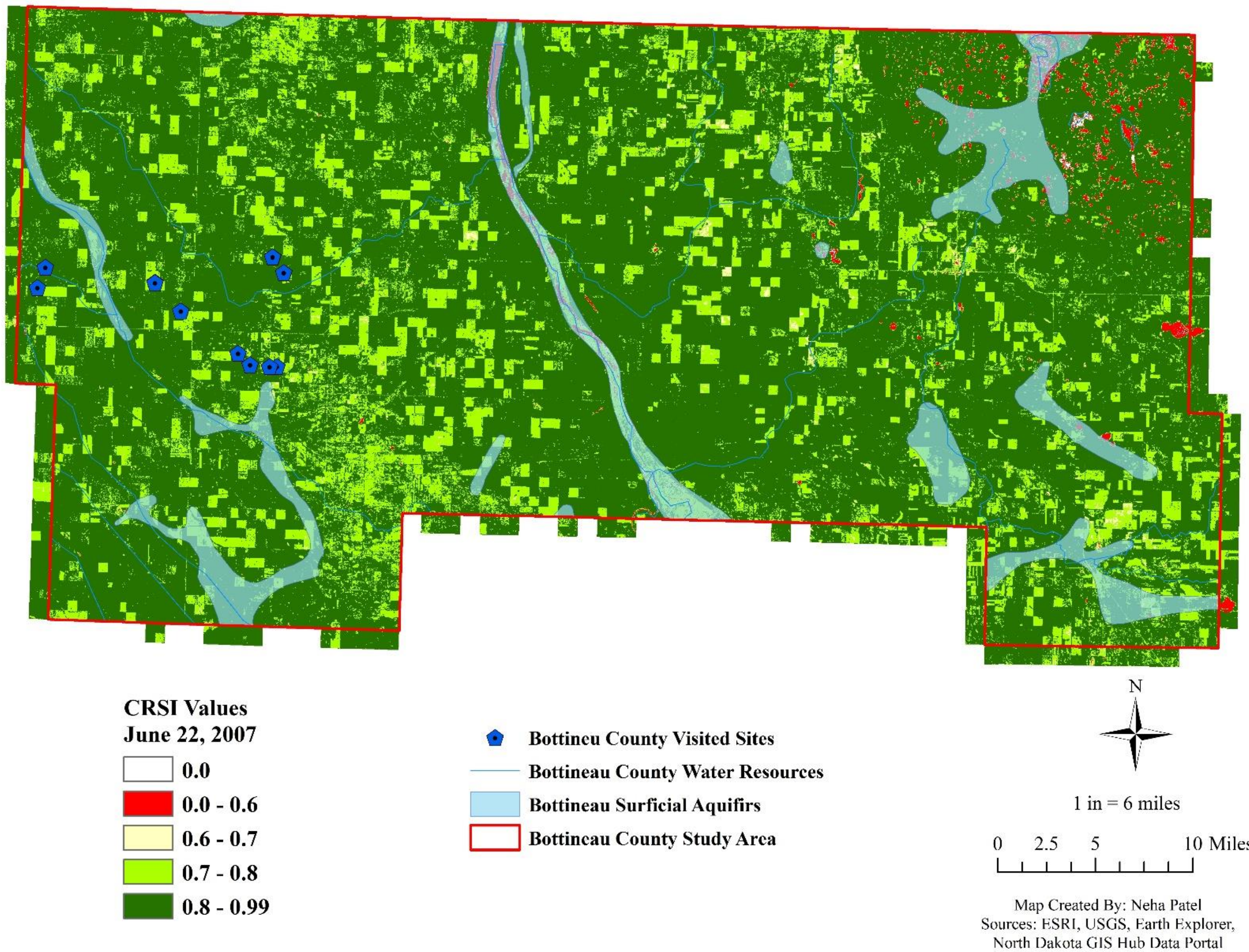

Figure 4.16: Bottineau County CRSI Values on June 22, 2007.

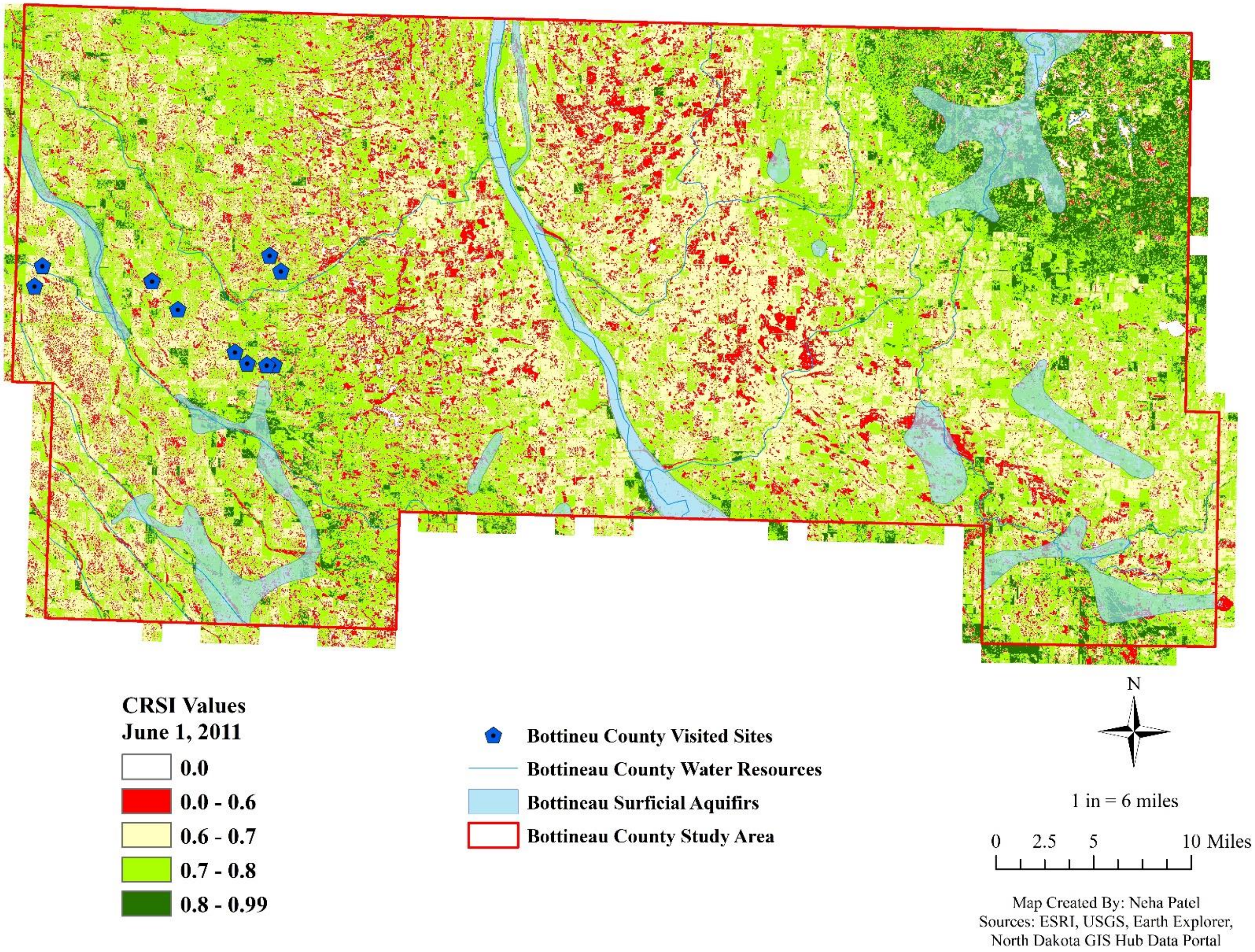

Figure 4.17: Bottineau County CRSI Values on June 01, 2011.

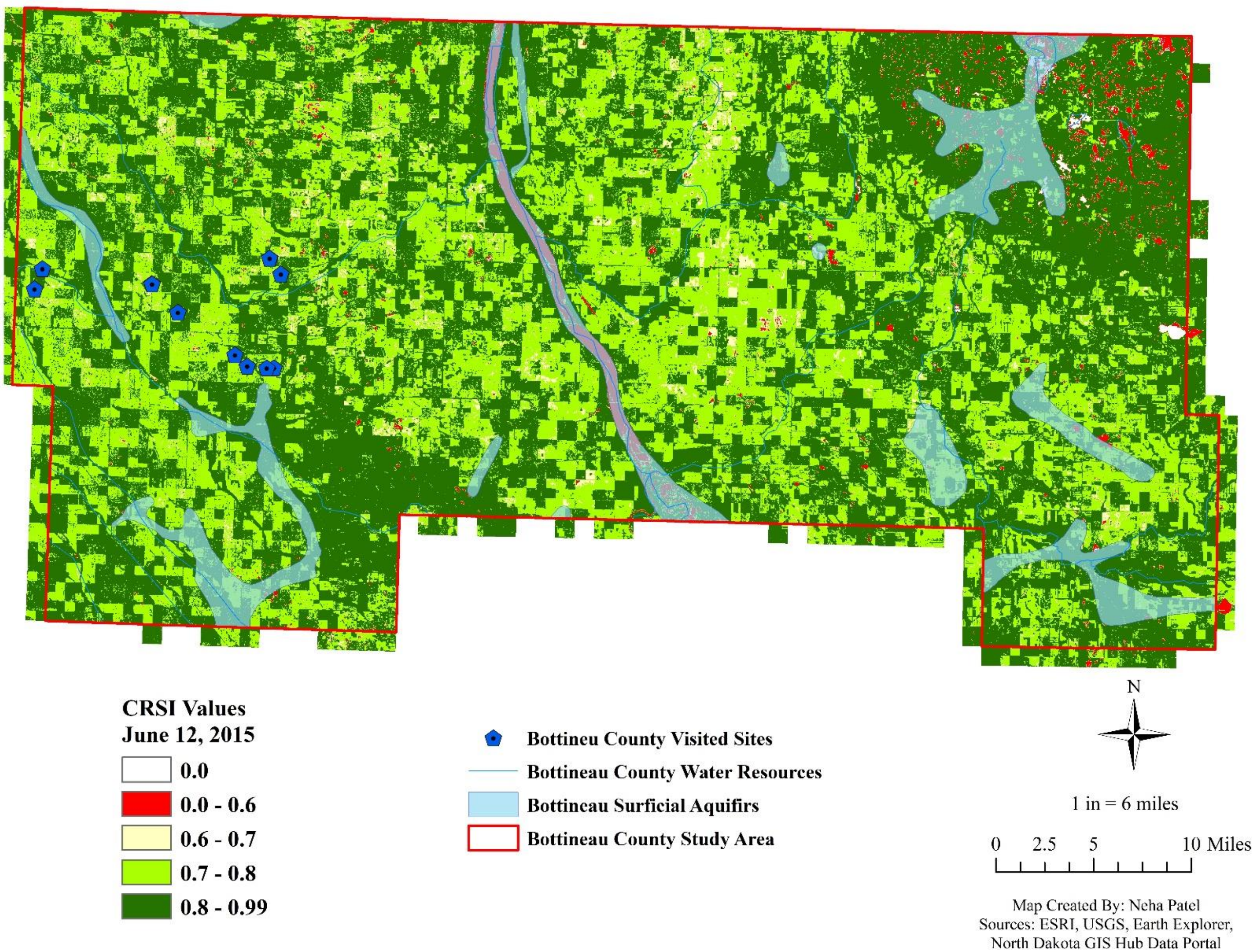

Figure 4.18: Bottineau County CRSI Values on June 12, 2015.

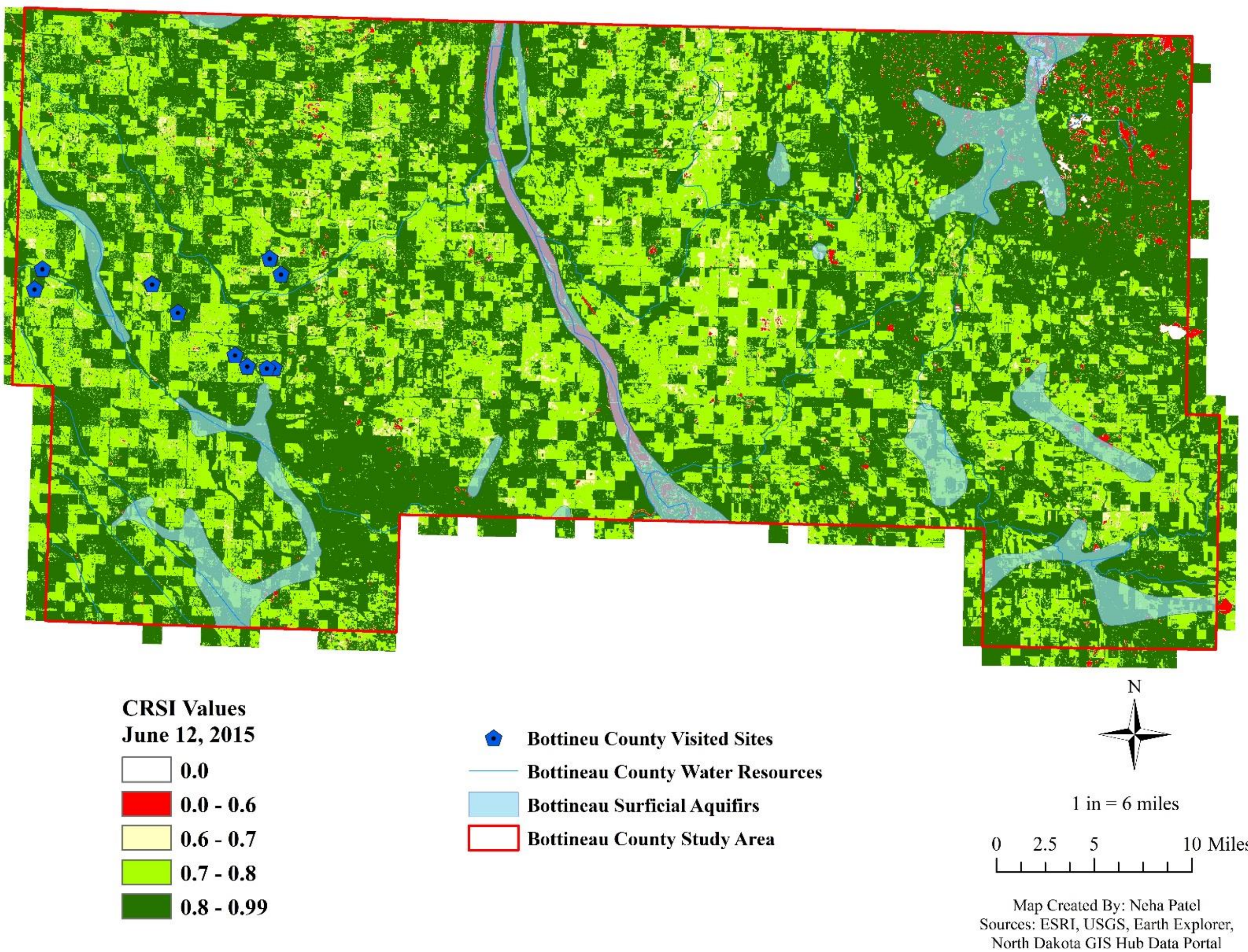

Figure 4.19: Bottineau County CRSI Values on June 30, 2016.

4.5 Selected Brine Spill CRSI Statistical Analysis

Statistical analysis (Mann-Kendall, Kendall's Tau and regression analysis) of 197 known spill locations versus CRSI values before and after the initial spill period are shown in Appendix C and D. Illustrations of these results are shown below in Figures 4.20 through 4.29 for general data trend. The general data in Figures 4.20 to 4.29 shows the upwards and downwards trends with increasing or decreasing CRSI values, respectively. The increasing trend shows significant improvement in land in spite of brine spills while decreasing trend shows unhealthy zones of vegetation areas. No trend shows the change in the farmland soils.

4.5.1 Mann-Kendall Test Observations for all 197 Location IDs Brine Spills (≥ 10 Barrels)

The analysis of CRSI values conducted for 197 location ID points of all 24 images in Bottineau County suggest that from all the CRSI data of 197 Incident ID presented, out of that about 60% location ID CRSI Values trend goes downward or negative, 30% show no change and about 10% trend shows an upward or positive trend. These data inference show that most of the farmlands adjacent to the brine spill locations have deteriorated over some time with lower CRSI values, which are directly connected to the "unhealthy vegetation." However, the downward trend in detail needs to be studied more extensively in terms of the total land change over the period. Some CRSI values show no change at known spill areas and may reflect land reclamation, or incomplete data or seasonal climate changes and variation, which might not have picked up the significant changes in CRSI values. Also, CRSI values showing upward trends indicate some improvement in the vegetation health, and may also reflect reclamation results. However, the upward trend change is only present in 16% of the total of 197 location IDs, where known spills are located. The Mann-Kendall and Sens slope analysis are less resistant to yearly variations in the data due to the way that they are calculated.

Mann-Kendall analysis Theil Sen's slop is depicted in the bold red color trend line. The trend line known as Sen's Slope or Theil-Sen line is a nonparametric alternative method to test trends The Sen's slope shows the trend at the median (50th percentile) concentration which changes linearly with time in Figures 4.20 to 4.29 respectively (Manley 2008).

4.5.2 Regression Analysis and Significance of P-values for the All Location IDs Brine Spills (≥ 10 Barrels)

Out of all data of 197 brine spills IDs, 76 (39% of data) incident IDs showed P-values less than 0.05, meaning significant slopes or tends. Out of all 197 location IDs of significance values, 41 location IDs have downwards trends, 13 location IDs with upwards trends and rest 22 IDs of p-values show no change in the data. Ideally, the R^2 values range from 0 to 1.00 show the percentage ratio of the minimum of 0% to a maximum of 100 %. The fitted R^2 values show how the proposed parametric data are fitted into the linear regression model. Also, small R^2 values do not mean the model is not good, and higher R^2 does not mean the model is the best-fitted model since the parametric analysis which helps to understand the validity of the model. The data used in this research show variation in R^2 values showed at maximum 10 % variation to the lowest almost 0%. This parametric method is highly influenced by yearly changes in CRSI values which are highly dependent on climatic conditions, drought conditions and reporting the exact locations of the brine spills in a more precise parametric method which is different from above Mann-Kendall nonparametric methods. Since the regression model depends on Mean Squared Error (MSE), Root Mean Squared Error (RMSE) and ratio of Standard Deviation, in this case this regression model helps us to understand the statistical validity of results based on R^2 and P values (Manley 2008; Scudiero, Skaggs, and Corwin, 2015).

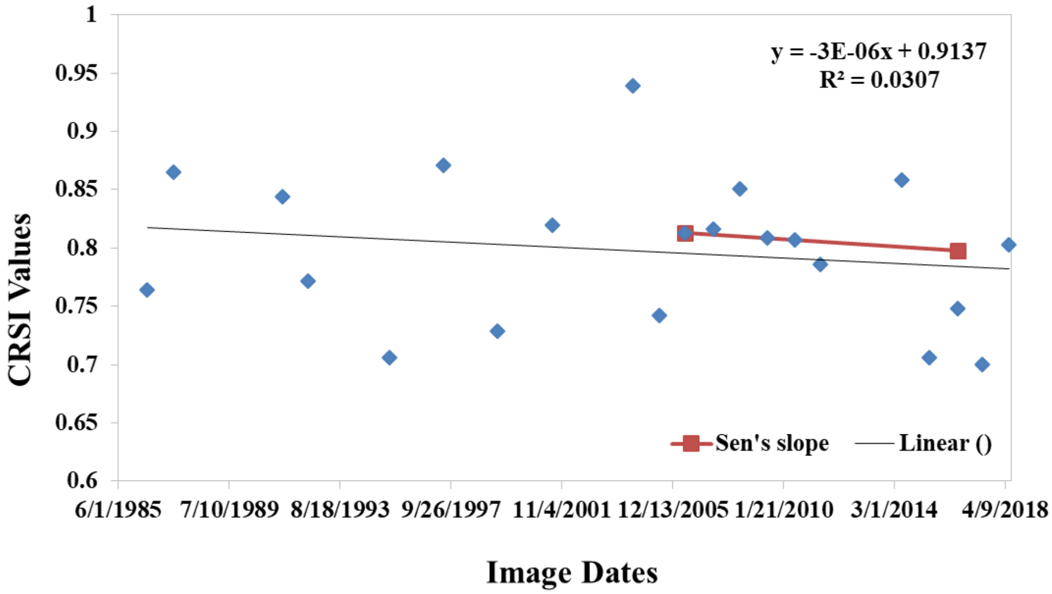

Figure 4.20: Oil Well Facility Nelson #2-13 SWD Location ID CRSI Values.

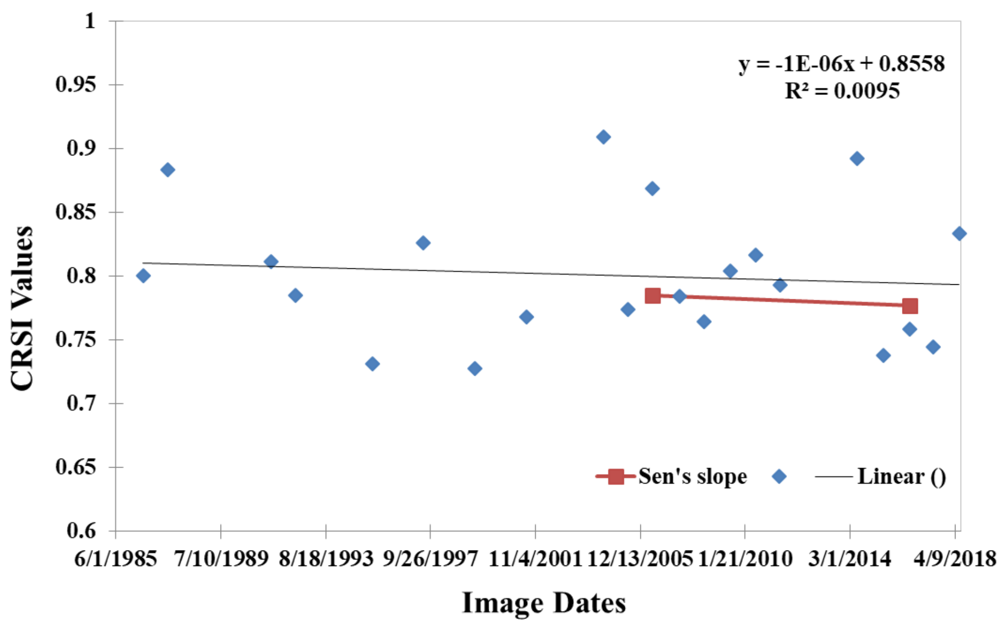

Figure 4.21: Oil Well Facility TRENDSKAADEN 44-282 Location ID CRSI Values.

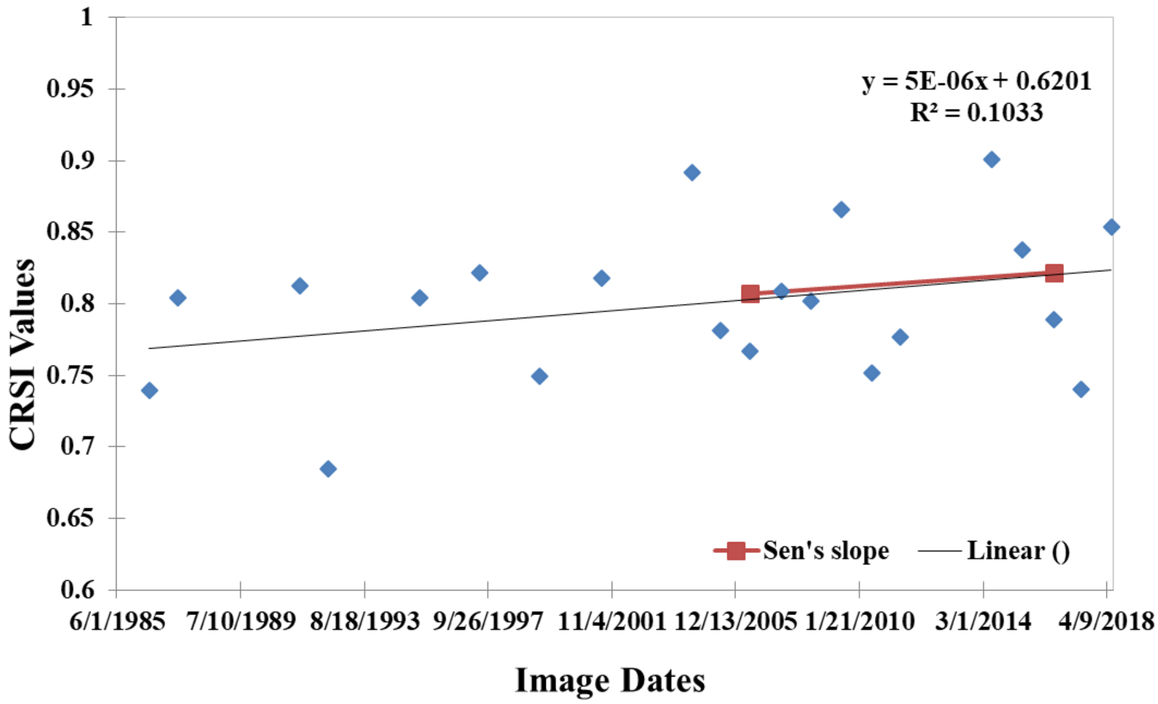

Figure 4.22: Oil Well Facility RICE-STATE 2H Location ID CRSI Values.

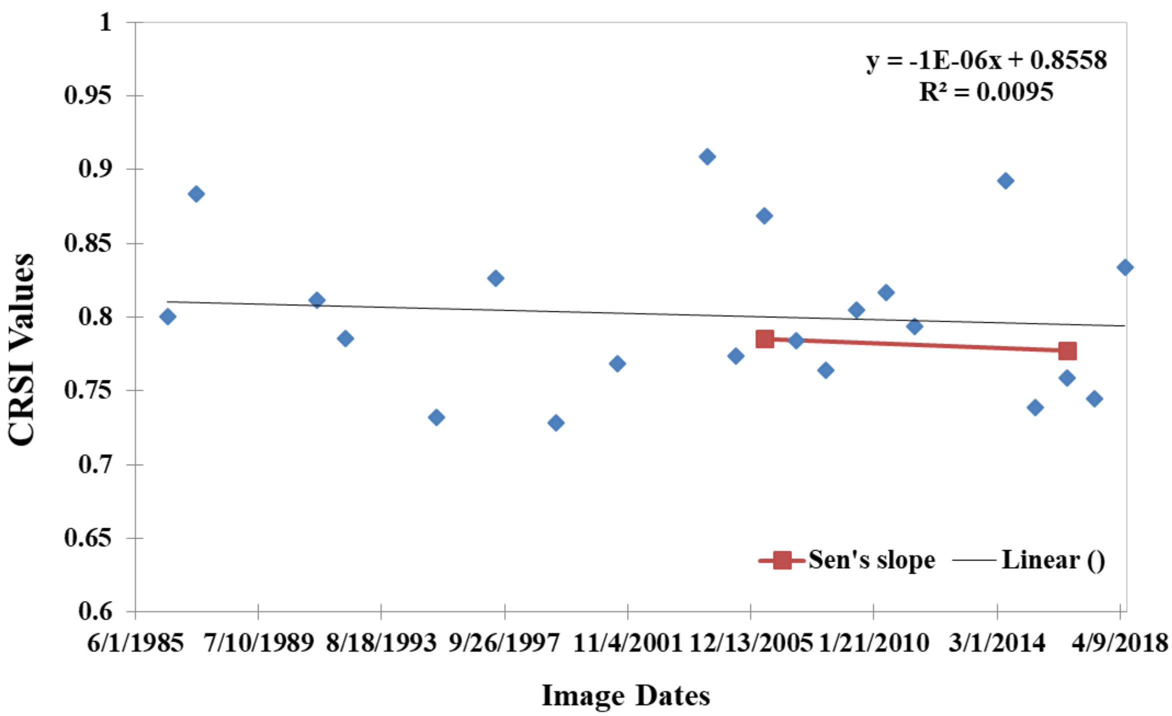

Figure 4.23: Oil Well Facility Madsen CTB Location ID CRSI Values.

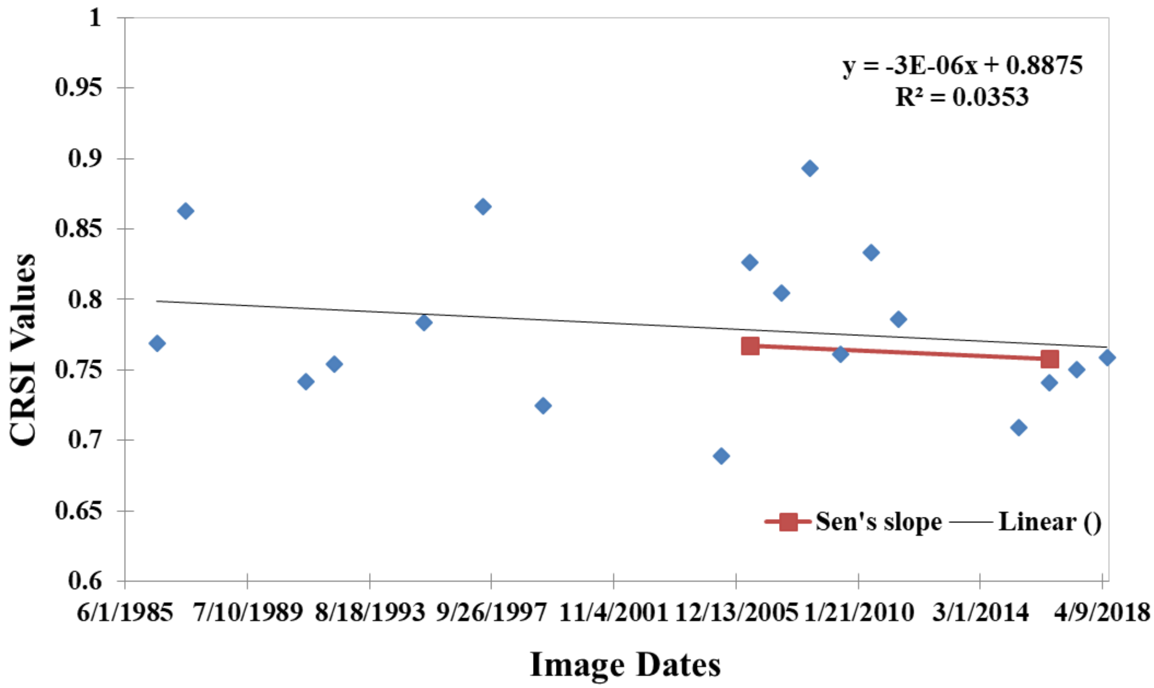

Figure 4.24: Oil Well Facility Wilms Injection Plant (Wilms) Location ID CRSI Values.

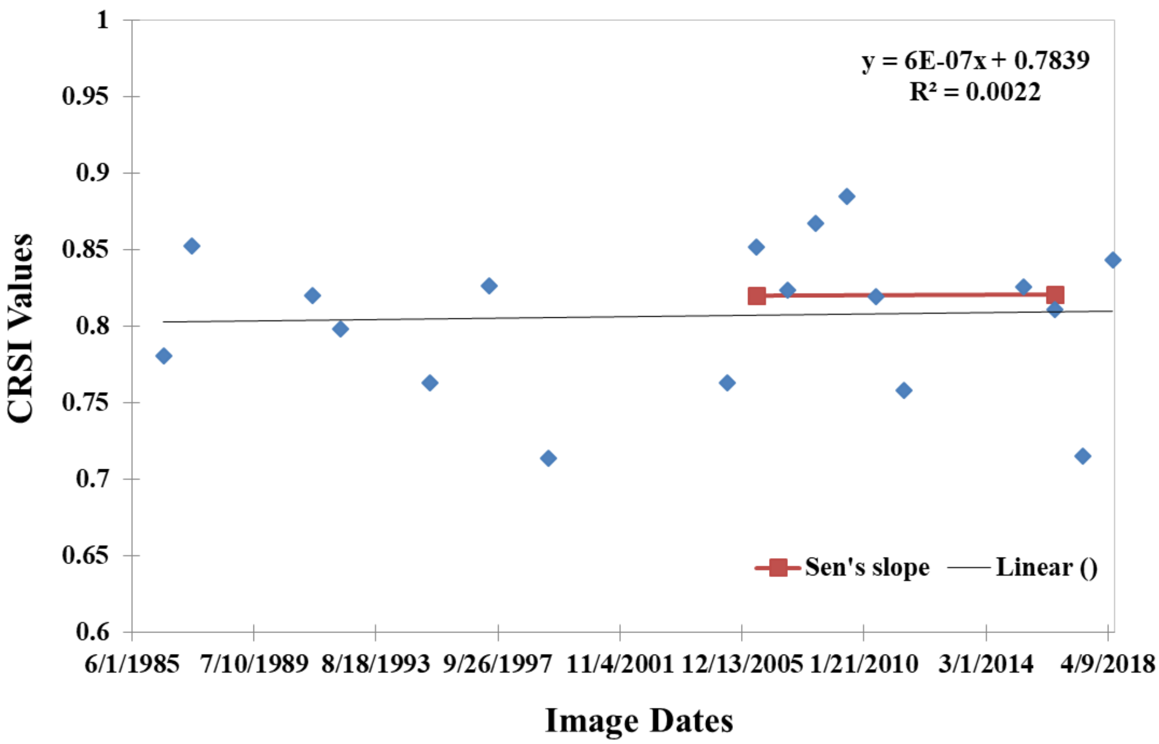

Figure 4.25: Oil Well Facility CRAMER 1 SWD Location ID CRSI Values.

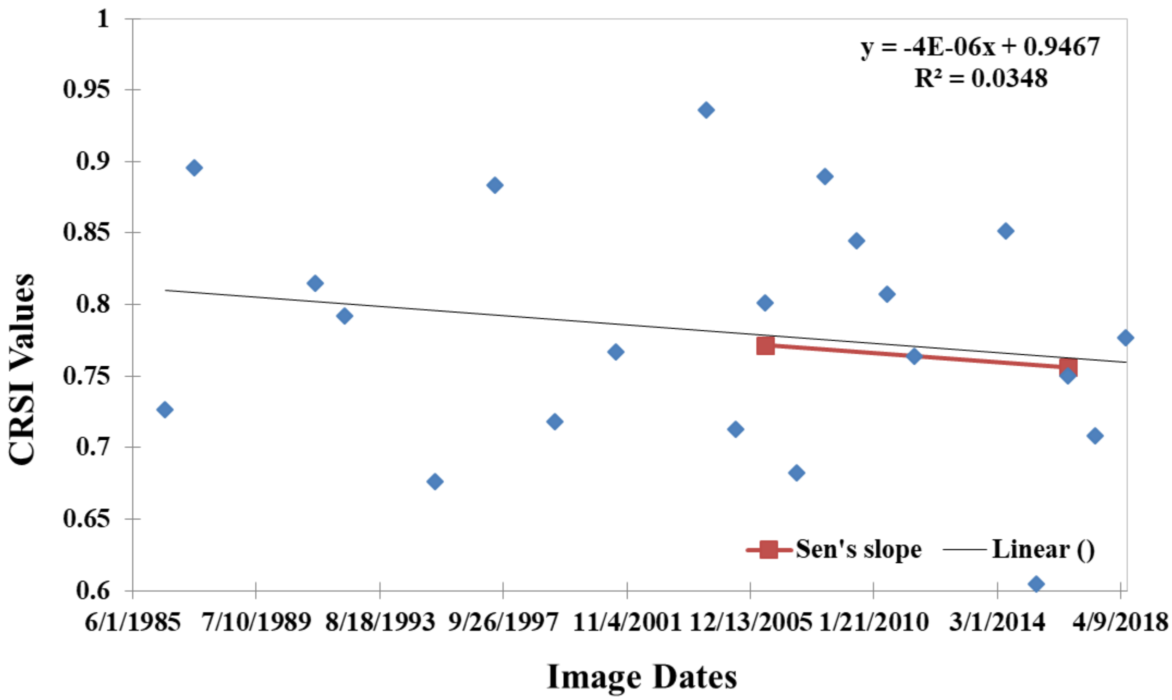

Figure 4.26: Oil Well Facility near Incident ID 1994 CRSI Values.

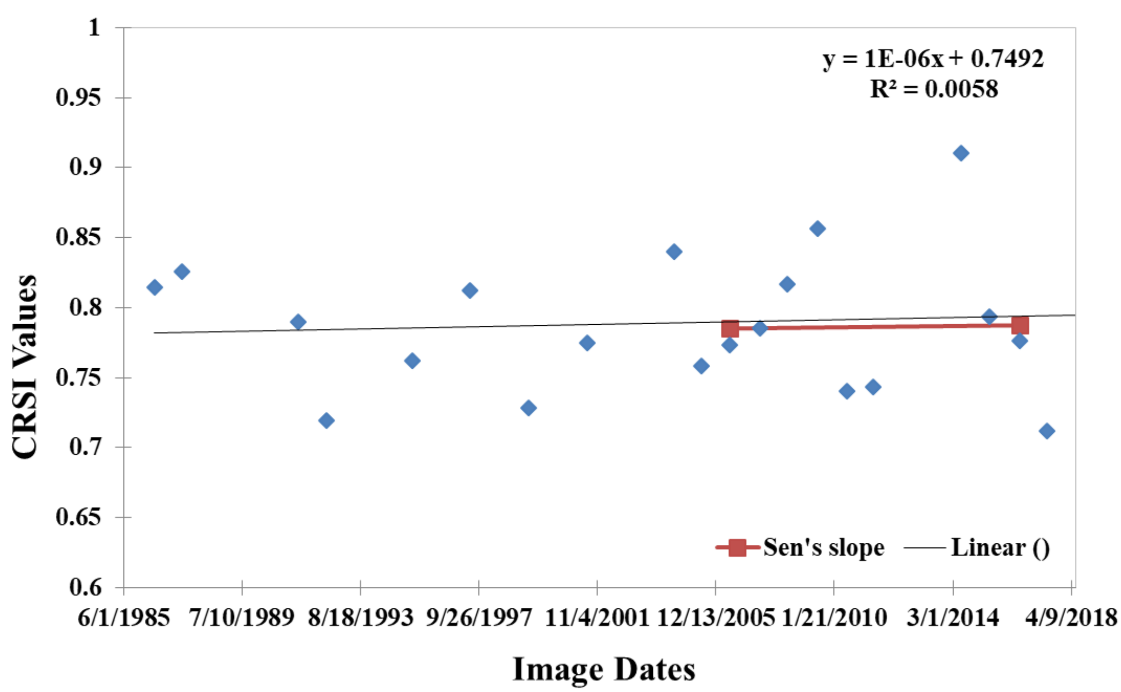

Figure 4.27: Oil Well Facility PETERSON 2 Location ID CRSI Values.

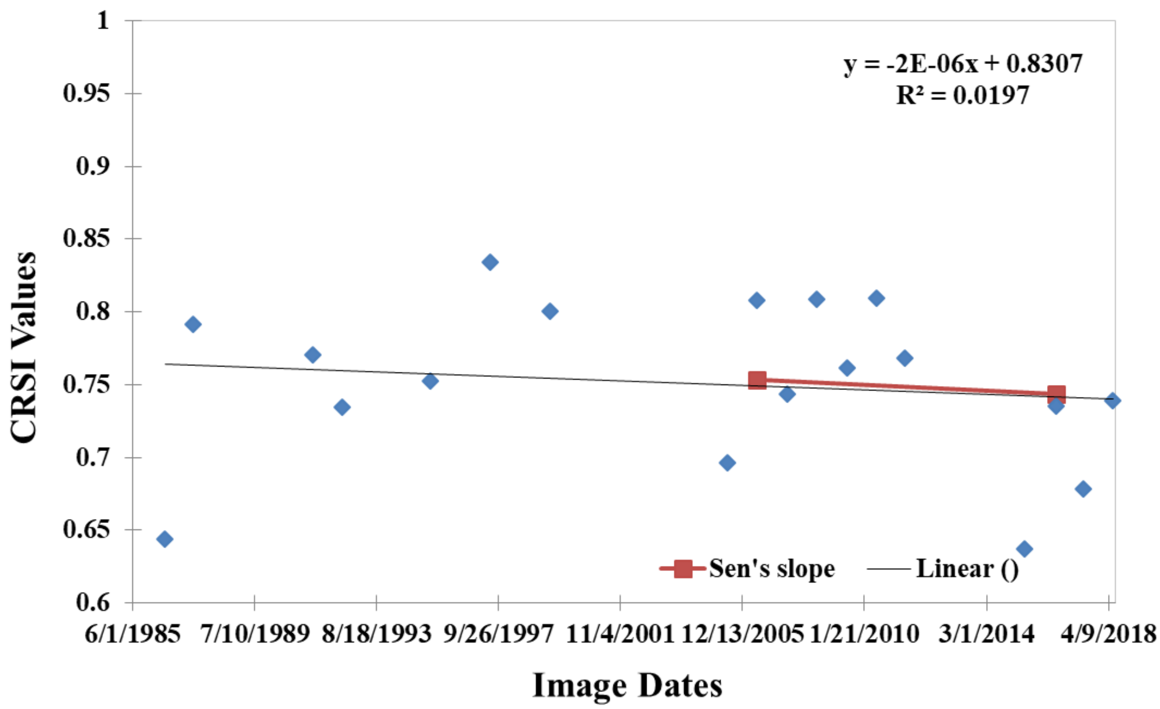

Figure 4.28: Oil Well Facility Haugen BCTB Location ID CRSI Values.

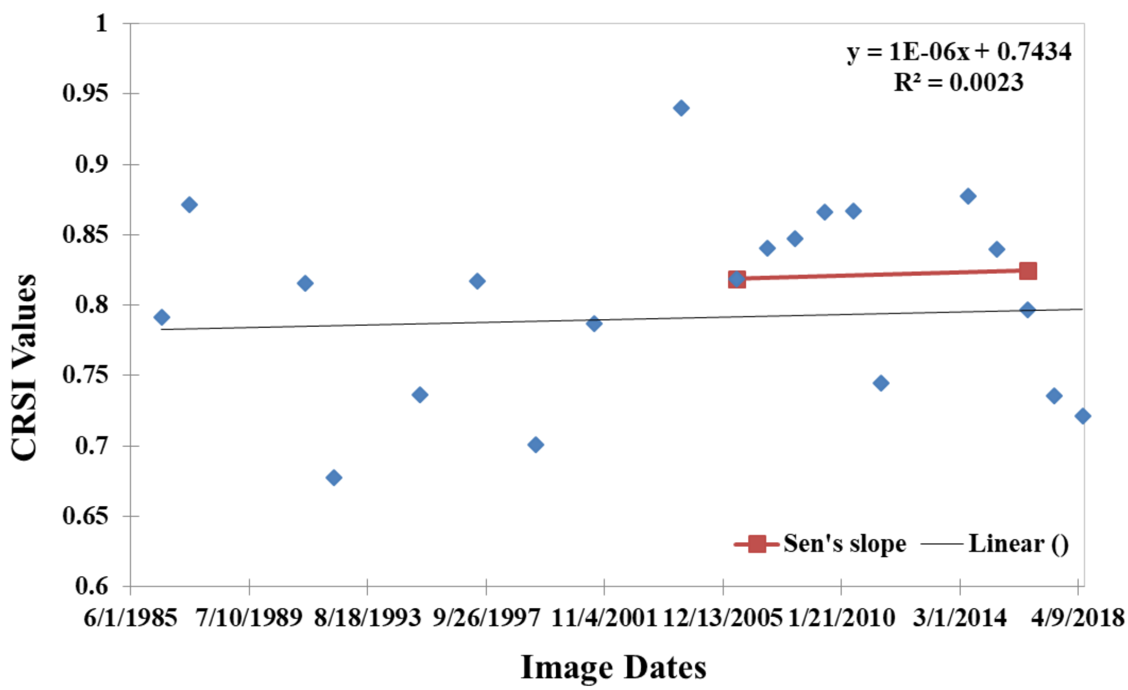

Figure 4.29: Oil Well Facility near Incident ID 1102 CRSI Values.

4.6 The Observation of Mean CRSI Difference between Severely Drought and Non-Drought Years

Out of all total 24 raster images of CRSI values ranging from 1982 to 2018, the two years of 1988 and 1989 June months' Landsat images were with higher PDSI values of -5.44 and -2.76 respectively removed as high negative PDSI values, which affect the dryness of region in Bottineau County (Figures 4.30, 4.31). The PDSI data was taken into consideration in order to minimize the error zone in terms of understanding soil salinity since drought impacted dry regions can display soil salinity effect in CRSI values and skew the outcome of the result. CRSI mean values were calculated for all years raster images from 1982 to 2018 with PDSI drought effected years and without PDSI drought effected years to understand the time-based change on the soil salinity on farmlands before and after removing drought-affected years. The result in Figure 4.33 shows that the difference in cropland change appears as minimal and not very significant since the drought years with high negative PDSI values are only for two limited years. In the future, in order to find more significant changes and differences, more harvesting season data and Landsat imagery with more significant data ranges to compare with more PDSI drought-affected years would show more significant and precise results.

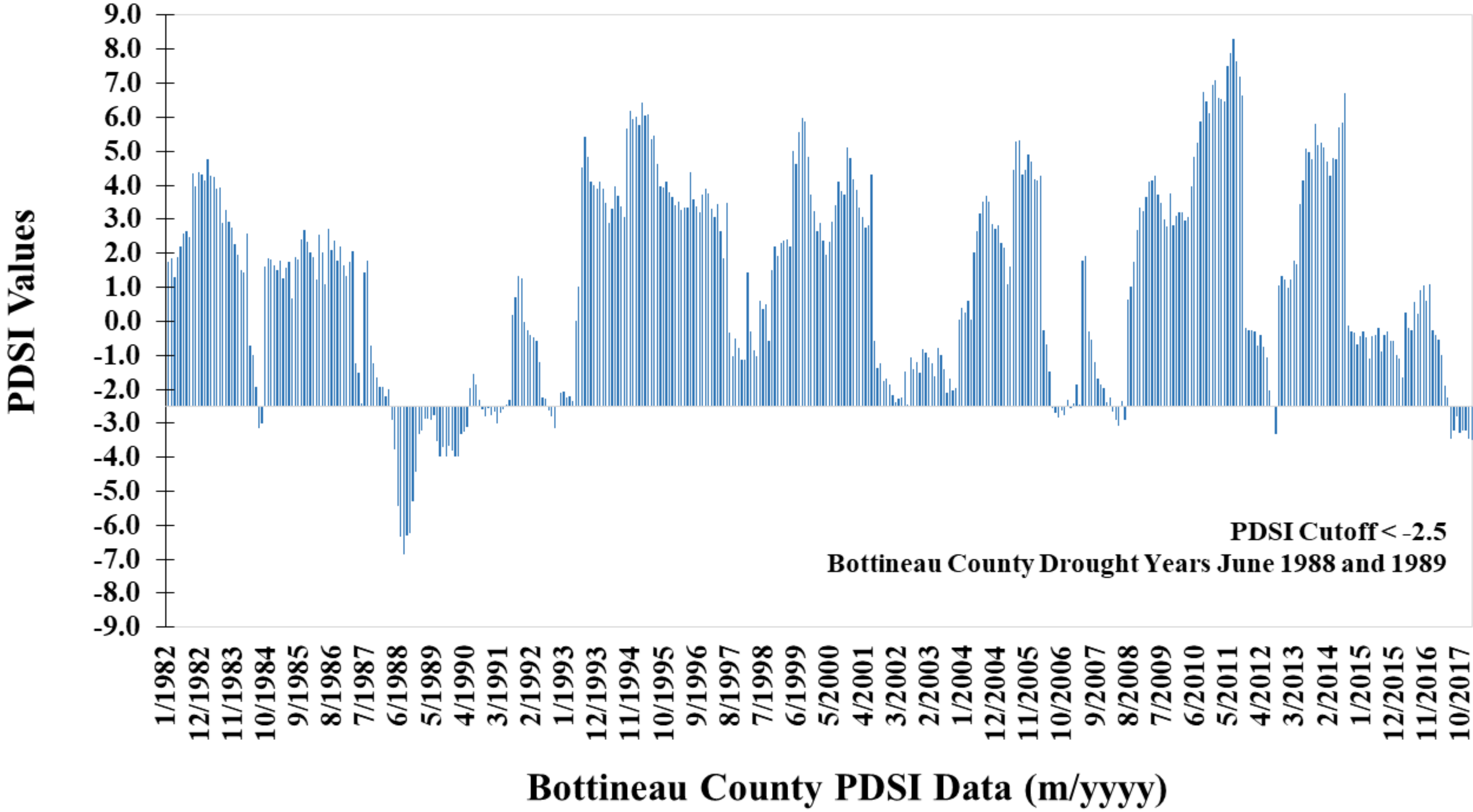

Figure 4.30: Bottineau County Palmer Drought Severity Index (PDSI) from Years 1982 to 2017.

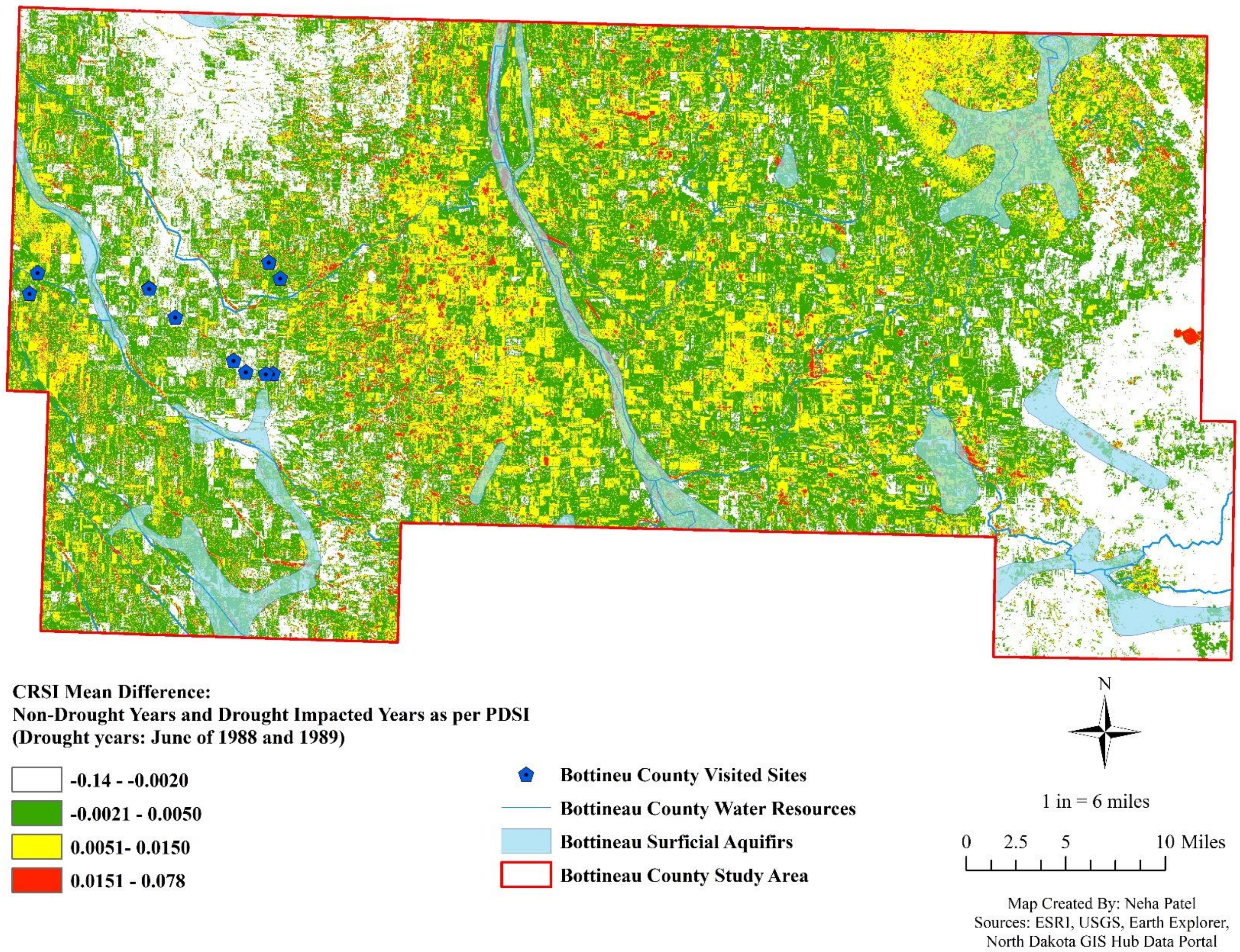

Figure 4.31: Bottineau County CRSI Mean Difference Values between Non-droughts Affected Areas and Drought-Affected Areas.

4.7 Time-Based CRSI Values Observations near Well ID Nelson #2 13 SWD Before and After 2100 Barrels Brines Spilled in Sept 2004

The oil well location ID Nelson #2 13 SWD is located in the township 159, range 82 and section 13 of Bottineau County in Northwest quarter section and a southwest quarter-quarter section at the geographic coordinates of 48.60 N and -101.21 W latitude and longitude respectively (Figures 4.32 to 4.35). This well ID had the highest 0.33 million liters (2100 barrels) of brine spills in September 2004.

The CRSI values in the zoomed in location shows gradual deterioration of farmland vegetation. In Figures 4.32 and 4.33, the images before brine spills in 2001shows green, healthy vegetation farmland with higher CRSI values mostly above 0.7; however, the next Figure 4.34 and 4.35 CRSI images from June 2005 shows low CRSI values in red color patches. Also, clear Landsat images from subsequent years of June 2002 and 2003 were not available due to bad cloudy images, so the data is not continuous. However, Figures 4.34 and 4.35 depict CRSI values post-September 2004 larger brine spill of 0.33 million liters (2100 barrels) effect is visible as the deteriorating vegetation with lower CRSI values. Also, in the entire section of 0.65 million m^2 (160 acres) to 0.16 million m^2 (40 acres) there is more deterioration of the land progresses which can be viewed in these zoomed in images but indeed the zoomed out images in specific areas show lots of "unhealthy" saline patches with lower than ≤ 0.6 CRSI values. Figure 4.34 shows very significantly low CRSI values after spills in September 2004, depicted in "red" color. However, in Figure 4.35 shows low CRSI values with CRSI values between 0.6, 0.7, and red patches with less than 0.6 values show in Figure 4.35 visible two years after the brine spills.

The soil is impacted, and the farmland deterioration is visible in these areas with lower CRSI values, suggest that the land reclamation efforts may not be working effectively as it should in these areas. Thus it also shows that the reclamation process is lengthy and costly and mostly less effective for large spills (Doll et al., 1985; Murphy and Kehew, 1984; VanderBusch 2017). Also, the local farmers reported that the land reclamation efforts have miserably failed in the areas with abandoned dry, salts patch land which is widely reported in several news articles (Murphy et al.1983; Murphy 1988; Dalrymple 2014; Gottesdiener 2014; Butchireddygari 2018; Meehan et al. 2017). The data shows that 121 old brine pits have been identified in Bottineau County surrounding areas which damaged approximately 5.9 million m^2 (1,450 acres) of farmland with 0.05 million m^2 (12 acres) average per farm site (Doll et al., 1985; Murphy and Kehew, 1984; Murphy 1988; Meehan et al. 2017; VanderBusch 2017).

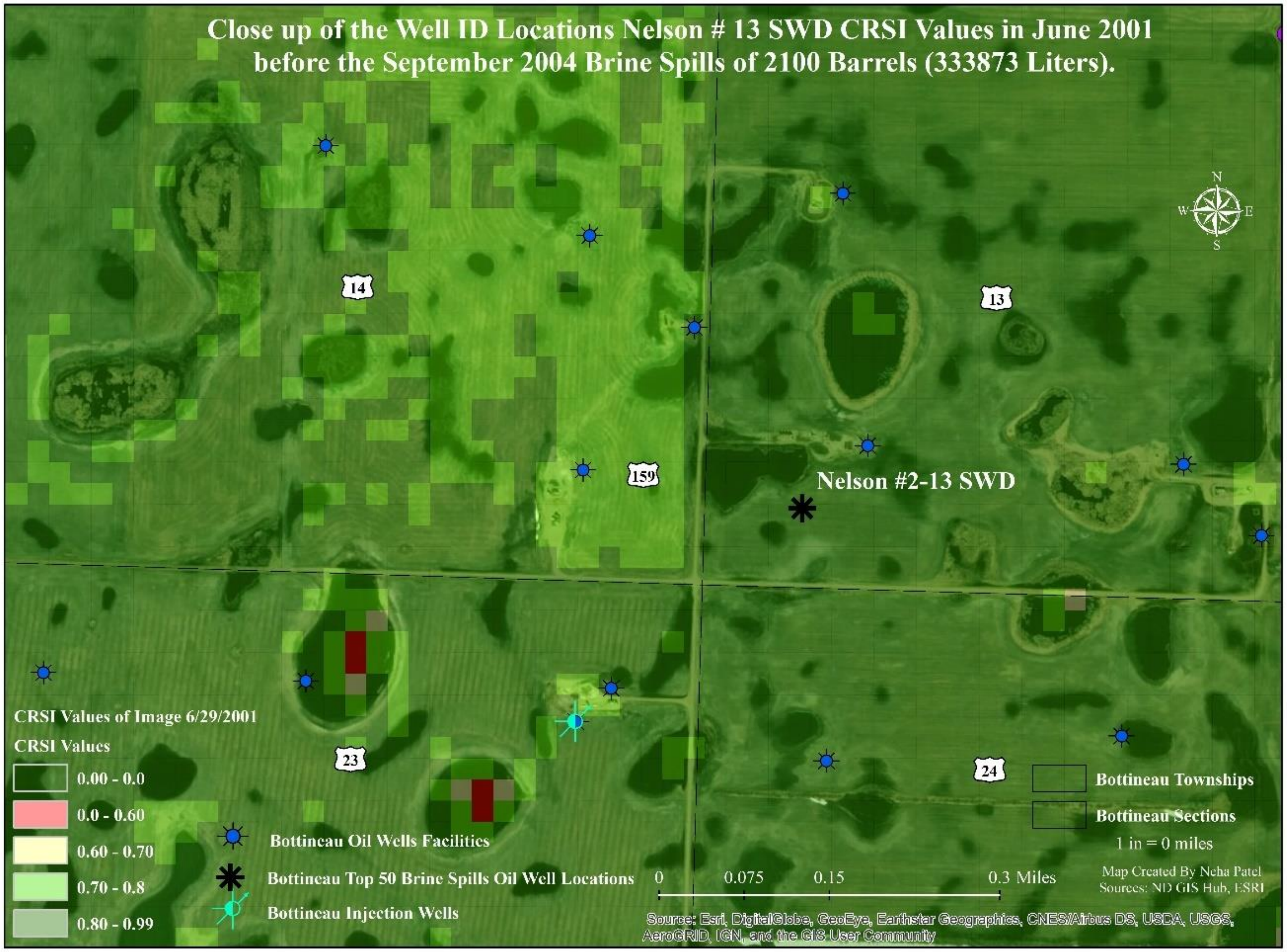

Figure 4.32: Close up of the Well ID Locations Nelson #13 SWD CRSI Values in June 2001 Before the September 2004 Brine Spills of 2,100 Barrels (0.33 million liters).

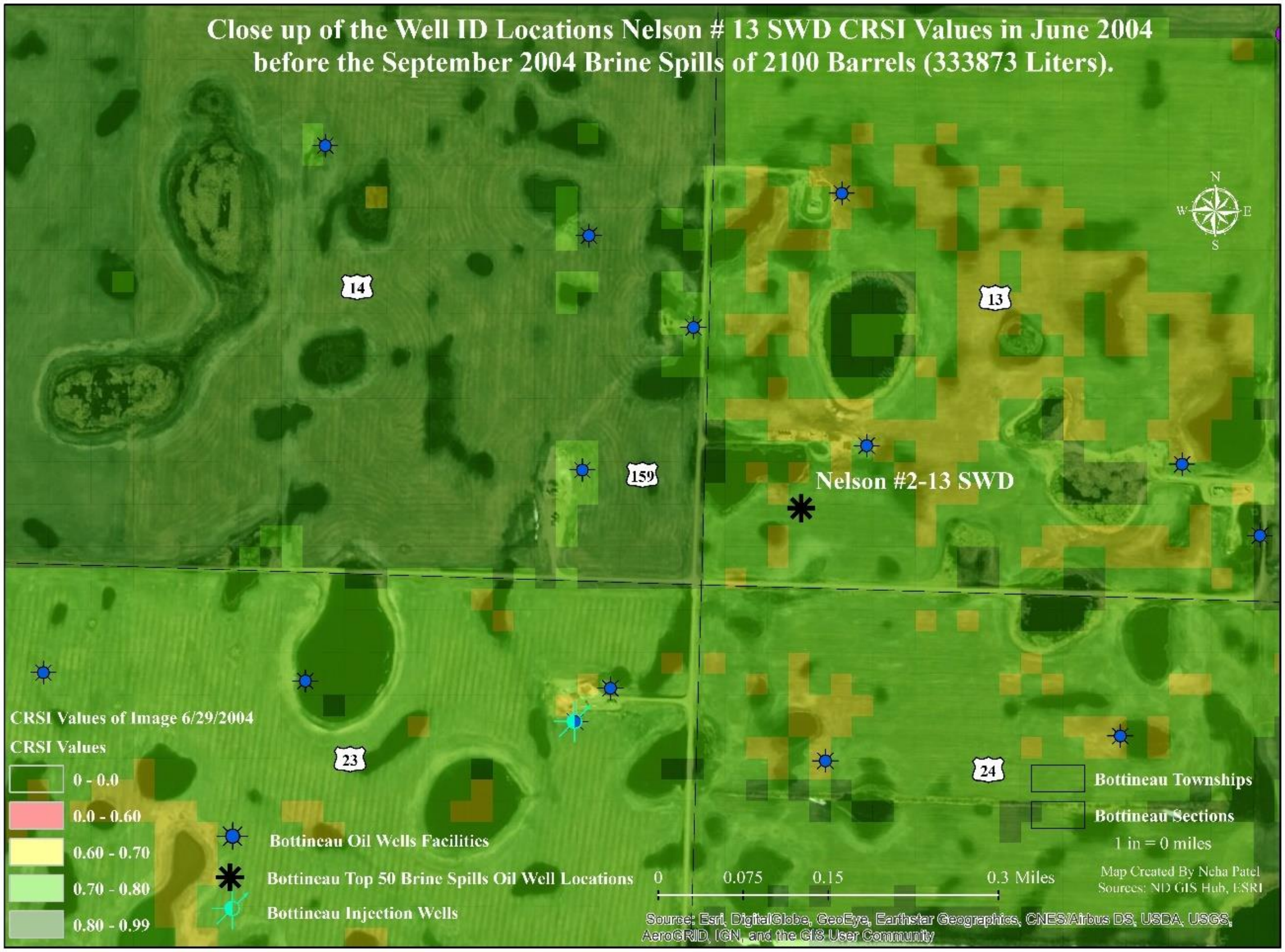

Figure 4.33: Close up of the Well ID Locations Nelson 13 SWD CRSI Values in June 2004 Before the September 2004 Brine Spills of 2,100 Barrels (0.33 million liters).

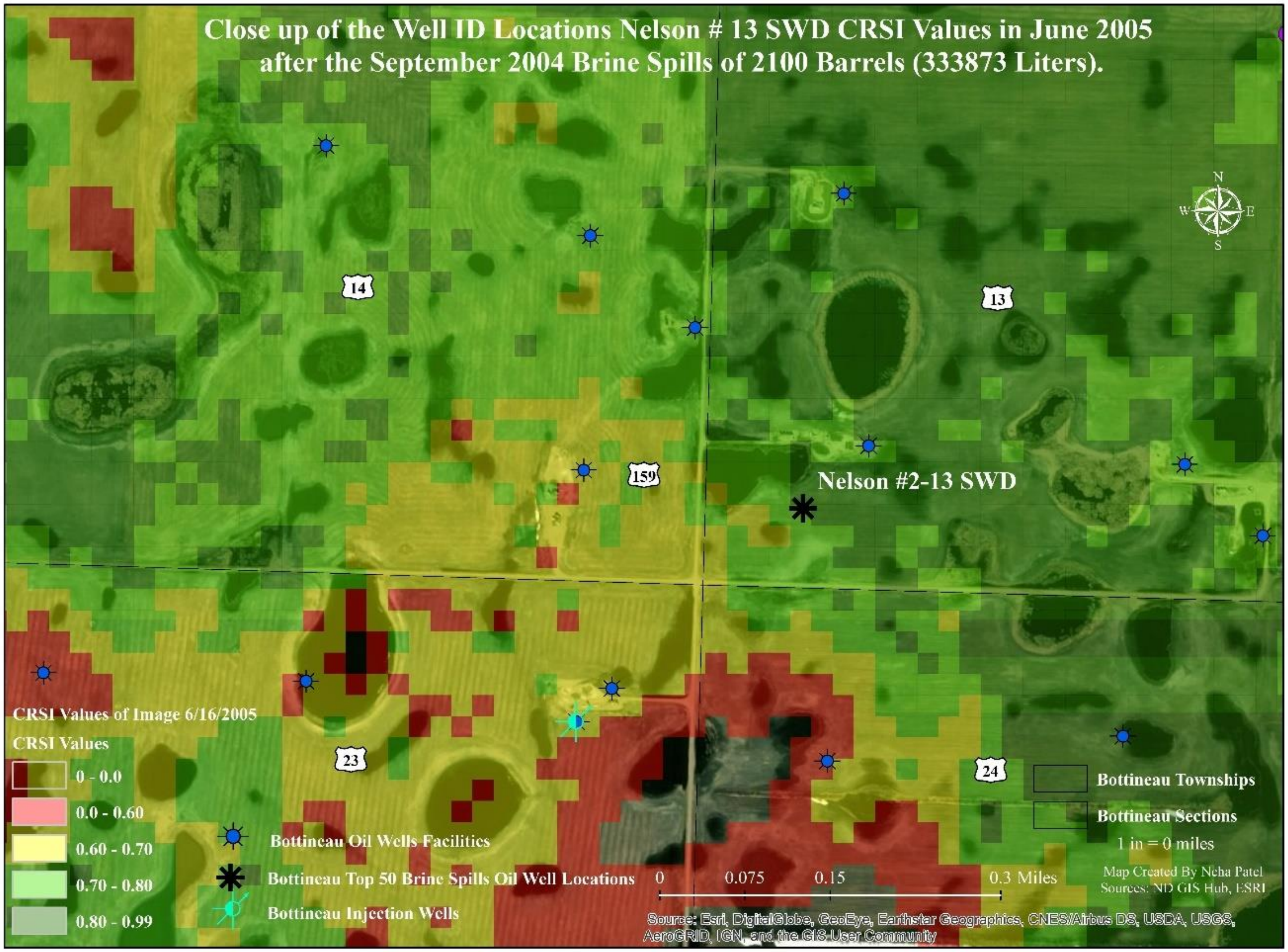

Figure 4.34: Close up of the Well ID Locations Nelson #13 SWD CRSI Values in June 2005 after the September 2004 Brine Spills of 2,100 Barrels (0.33 million liters).

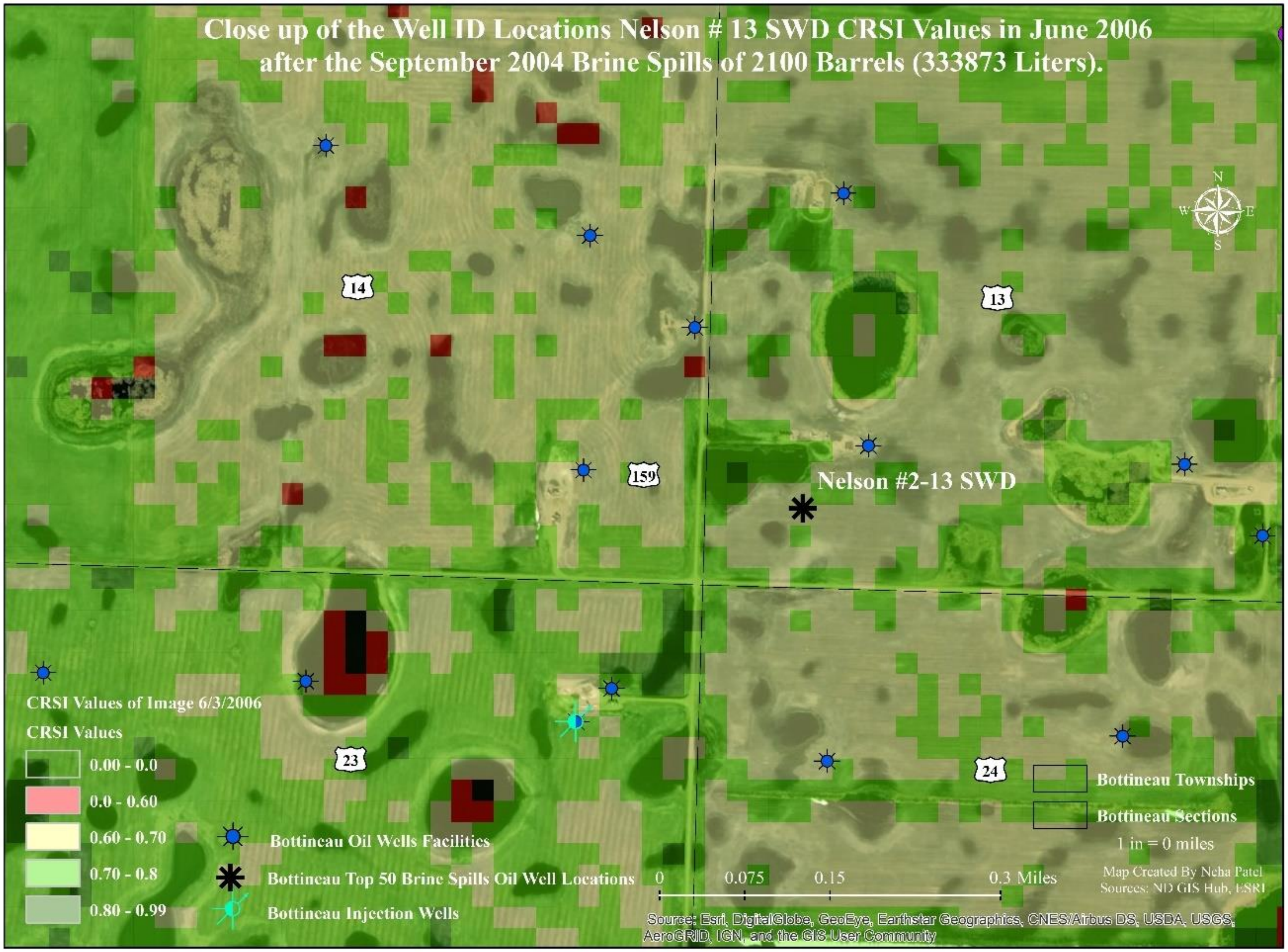

Figure 4.35: Close up of the Well ID Locations Nelson #13 SWD CRSI Values in June 2006 after the September 2004 Brine Spills of 2,100 Barrels (0.33 million liters).

4.8 Time-Based CRSI Values Observations near Injection Wells Located Adjacent to Visitation Sites before and after 2003 and 2004 Brine Spills

The below-given table 4.5 shows the coordinates of visitation sites ID six, seven, eight and nine

Table 4.5: Visited Impacted Sites near Injection Wells, Bottineau County.

Site ID	Latitude	Longitude	Elevation	Visitation Date
6	48.75	-101.25	458.28	9/16/2016
7	48.74	-101.23	464.60	9/16/2016
8	48.74	-101.20	457.93	9/16/2016
9	48.74	-101.21	460.95	9/16/2016

The maps of Injection ID wells located near Bottineau County in above-visited sites near injection well ID show the time-based changes in CRSI values over the period (Table 4.5; Figure 4.36 to 4.40).The purpose of Figures 4.36 to 4.40 is to cover the visitation sites and spills near which are surrounded by approximately 13 location well IDs, one injection well and one major spill location IDs. The areas near location IDs had approximately 0.54 million liters (3300 barrels) “reported” small and big brine spills between the years 1999 and 2003. In Figure 4.36, the areas near visited sites have higher CRSI values showing green vegetation areas in the harvest season of June 1999. However, CRSI values in Figure 4.37 June 2000 where the Figure shows a cloud patch is considered as the data error but in the right side but in the middle low CRSI values are visible (Figure 4.37). The data suggest that in 1999 and 2000 years, the areas spilled 190 barrels approximately processed and Dakota waters in these areas. This lower CRSI values may be due to above spills effect and also “under-reporting “and “no reporting” brine spills below 10 barrels brine spills effect. Also, subsequently the area wise fluctuation of CRSI values is notable in Figures 4.38 and 4.39 respectively from years June 2001 and 2004 before and after spills respectively in terms of vegetation is visible over the period. The healthy green zones ≥ 0.8 and above CRSI values are decreasing adjacent to these injections wells showing deteriorating CRSI values from 0.6 to 0.7 as “borderline” of unhealthy zones (Figures 4.37, 4.38, 4.39). Also, in the year 2005 (Figure 4.40), the red color, “ unhealthy” zones patches showing CRSI values ≤ 0.6 near visitation sites clearly show brine spills impacted sites adjacent to the injection wells.

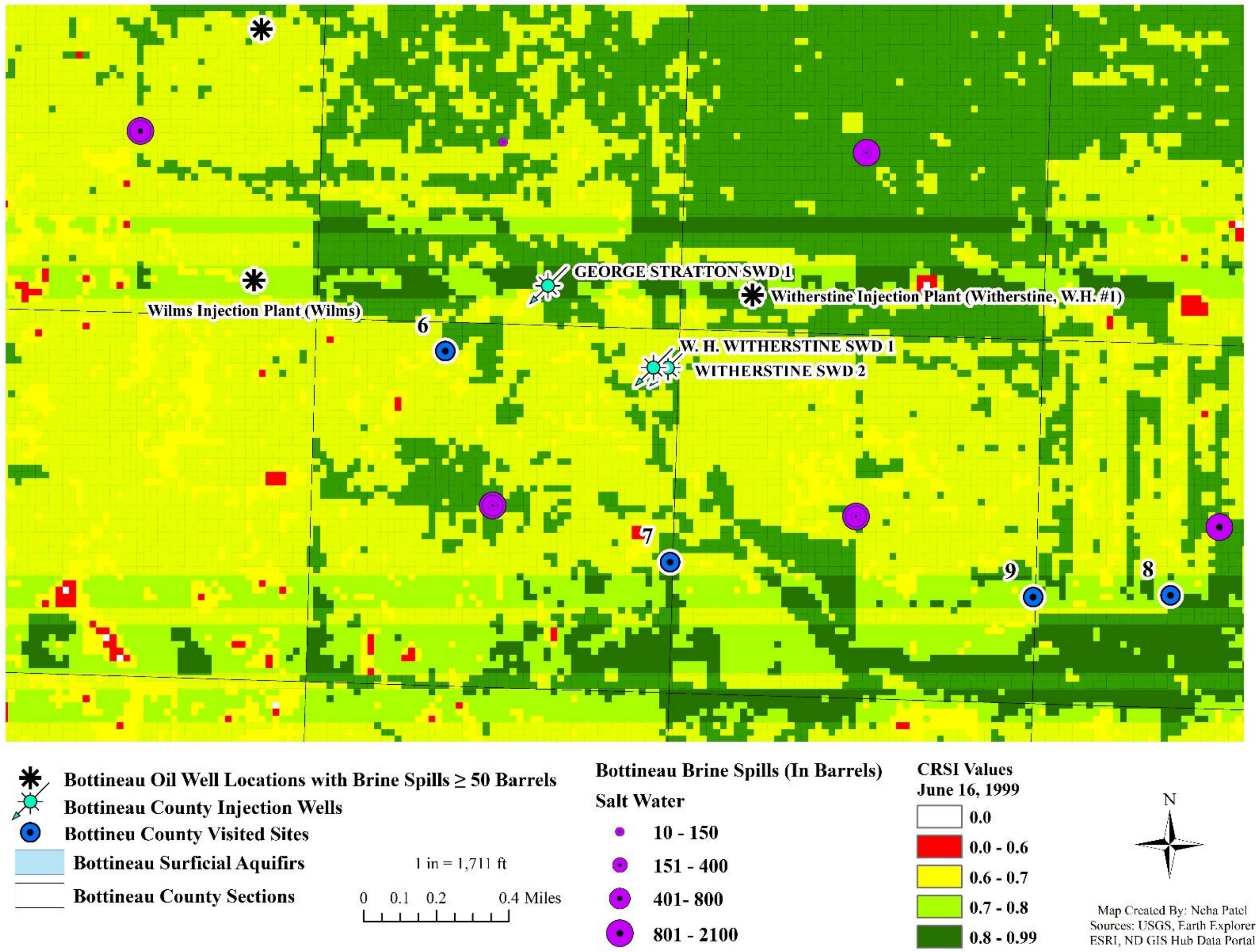

Figure 4.36: Close up of the well ID locations CRSI values in June 1999 near the visited sites before the 2003 and 2004 brine spills.

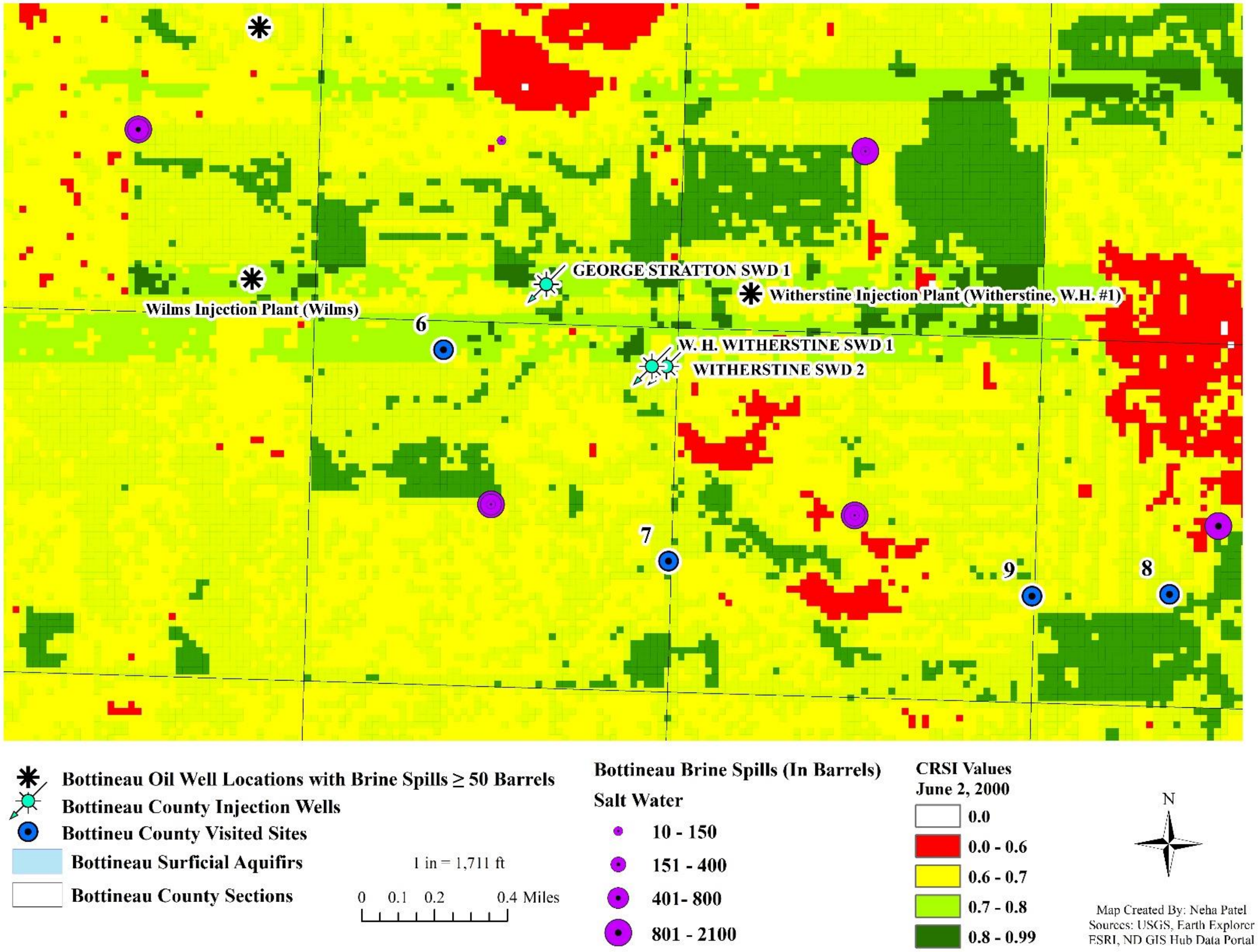

Figure 4.37: Close up of the well ID locations CRSI values in June 2000 near the visited sites before the 2003 and 2004 brine spills.

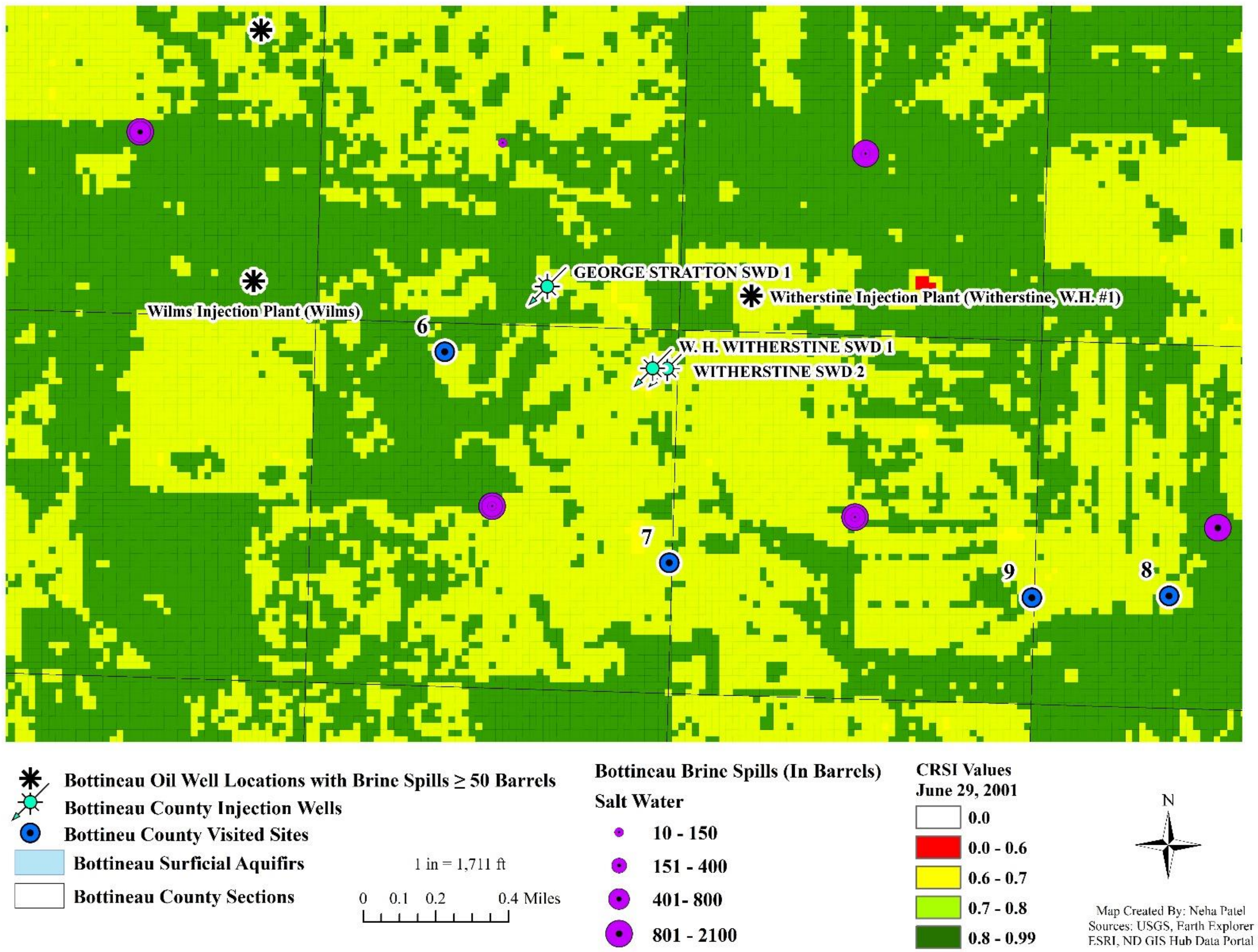

Figure 4.38: Close up of the well ID locations CRSI values in June 2001 near the visited sites before the 2003 and 2004 brine spills.

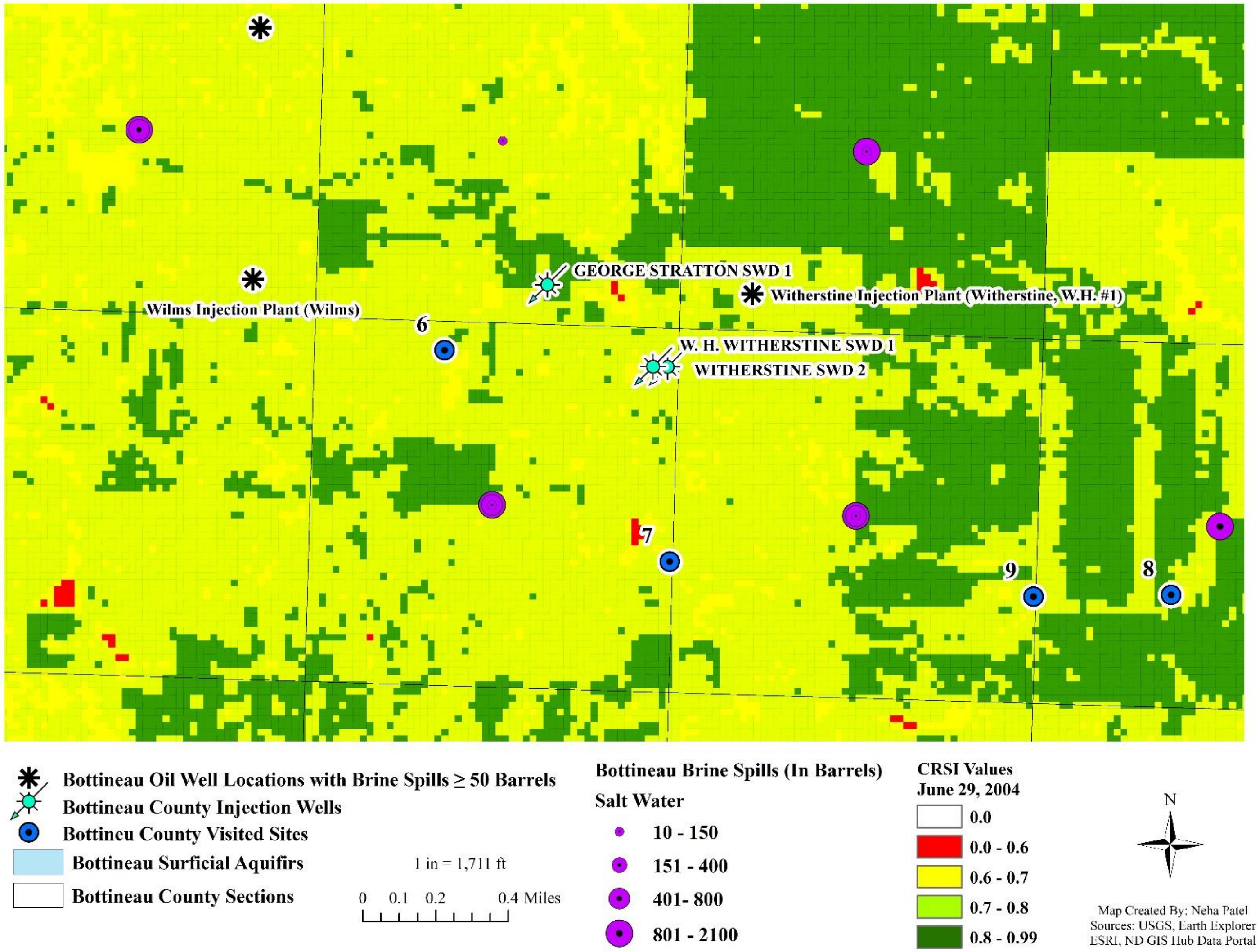

Figure 4.39: Close up of the Well ID locations CRSI values in June 2004 near the visited sites after the 2003 and 2004 brine spills.

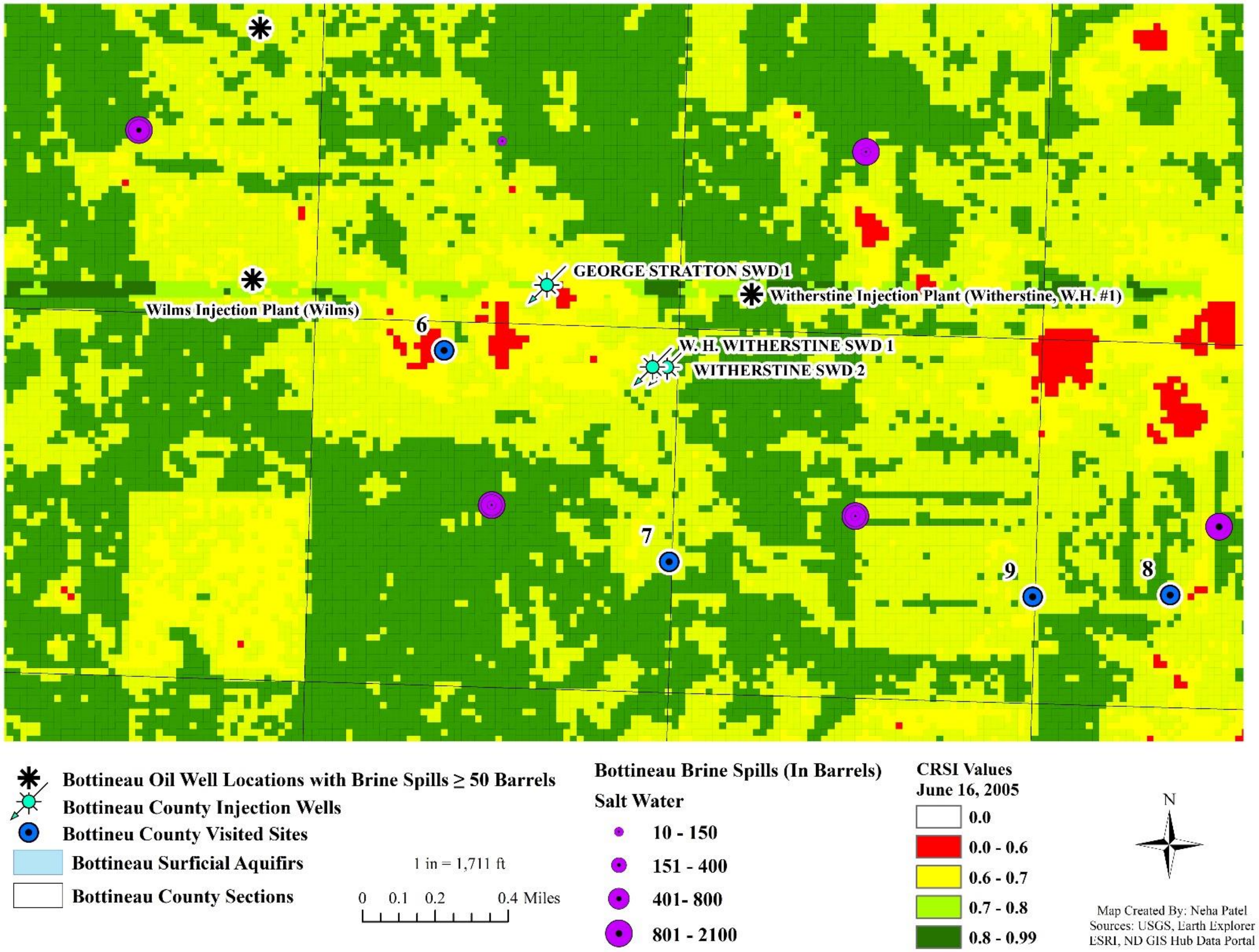

Figure 4.40: Close up of the Well ID locations CRSI values in June 2005 near the visited sites after the 2003 and 2004 brine spills.

Chapter 5

Conclusions

5.1 The Bottineau County Spill Statistics

Bottineau County reported has 2,488 oil wells producing approximately 20.91 million liters (131,535 barrels) of oil as per month as shown in Figures 3.1- 3.3 (EERC, 2015; Oil & Gas Data, ND 2017). The County had reported a total of about 575 brine, and crude spills incidents between 1975 to 2017. Out of all the spills, 352 were crude spills, while 347 were brine spills (NDDH, 2017). This comes to 3.8 million liters (23,912 barrels) in brine spills and 0.91 million liters (5,693 barrels) in crude spills. Out of 347 brine spills, 157 were contained spills. The volume of brine spilled is four times more than the crude spills (Appendix B table). As per this data, the total number of brine spills have increased consistently every year from 1991 to 2016 (Figures 4.7-4.9). The individual month's data also shows increasing incidents from years 1991-2017. However, 1975-1981 and 1985-1990 showed a gap with zero spin values. In contrast to this reported gap, the incident Id reports presented in this thesis clearly show the occurrence of brine spill. The gap in the data reflects the underreporting or no reporting of the brine spills. Also, crude spills data show consistent increase in spill incidents since 1982 with few gaps between 1978 and 1981, 1984 and 1989 and 1998 and 1999 (Figures 4.8-4.10).The highest brine spills are noted at 0.33 million litres (2,100 barrels) on Sept. 20, 2004, followed by 0.24, 0.13, 0.11, 0.10, 0.09 million liters (1,500, 800, 700, 650, 600 barrels) on July 21, 2011, June 26, 2012, June 6,2014, Nov. 19, 2011, Jan. 6, 2004 and Oct.26,2012 (Figures 4.7,4.9). The largest crude spills are noted at 0.06 million liters (400 barrels) on Oct. 19, 1976, followed by 0.04, 0.03, 0.028, 0.025, 0.024, 0.023 million liters (260, 200, 175, 160, 155, 150 barrels) on Jan. 7, 2015, June 1, 1994, March, 13, 2008, March 9, 1976, Aug. 7,2001 and February 17,1976, respectively (Figurest 4.9, 4.11). Seventy-eightincident IDs out of a total of 575 (13.6%) had no clear cut crude spill information with "blank" data, which suggest the matter for more evaluation in terms of reexamining the spill reporting process since this absence of data in spite reported spill creates data error.

5.2 CSRI values trend analysis

The outcome of the analysis presented indicates that all Landsat scenes have a variation of CRSI values in Bottineau county where the lower CRSI values of ≤ 0.6 suggest that these farmlands, wetlands and many vegetation areas have been impacted by salinity adjacent to farmlands. Statistical analysis for this research study was conducted based on Mann-Kendall nonparametric method and Regression analysis P-value of the linear parametric method provided understanding related to the statistical trends. The results of CRSI values of 197 known spills before and after the initial spill period are shown in Appendix C and D.

The non parametric Mann-Kendall analysis and Sen's slope trend for 197 know spills of time based analysis of all 24 images (Figures 4.12-4.20; Appendix A) in Bottineau County suggest that about 60% of spills go downward or negative, 30% show no change and about 10% trend shows an upward or positive trend. The increasing trend shows significant improvement in land in spite of brine spills while decreasing trend shows unhealthy zones of vegetation areas. No trend shows the change in the farmland soils. These trend results are presented in the plots shown in Figures 4.20-4.29.

The parametric regression analysis of the data shows that out of 197 IDs, 76 incident IDs (39% of data) showed p-value less than 0.05, meaning significant slopes or tends, 41 location IDs have downwards trends, 13 location IDs with upwards trends and rest 22 IDs of p-value show no change in the data. The R^2 values showed a maximum 10 % variation to the lowest almost 0%. This parametric method is influenced by yearly changes in CRSI values and depending on monthly climatic conditions, drought conditions, and reporting the exact geo coordinate locations of the brine spills in a more precise parametric method. Thus, in most cases of location IDs, there are similarities between p-value analysis and Mann-Kendall analysis.

The Mann-Kendall analysis, Kendall's Tau, regression analysis, and p-value showed degradation in in vegetation growth due to soil salinity changes due to a decreasing trend in CRSI observed near spill areas adjacent to the oil well facilities. Detailed quarter-quarter mapping of brine spills based on pre- and post-spill CRSI value analysis at the specified location IDs significantly helped with understanding spatial variations and impact of the spills. Incident ID descriptions report document show brine seepages from unlined pit reserves, ruptured pipelines, spilling during transportation from a tanker or because of mishandling while disposing of saline water. All these issues have worsened this problem since the brine has penetrated in many farmlands and vegetation areas at the surface and subsurface level. Farmers in these brine spill-affected areas have been trying the remediation and reclamation process to save their farmlands, but in their experience, the effectiveness of the process have not been adequate in restoring the croplands to its original condition owing to soil dispersion and other salinity related physical properties alterations (Doll et al. 1985; Murphy and Kehew 1984; VanderBusch 2017).

The research shows that brine chemical composition near oil well facilities mainly consists of chloride and bromide ions (Doll et al. 1985; Lauer and Thamke 2014). The contents of sodium, magnesium, sulfates, chloride, carbonate, and bromide ions with total dissolved solid compounds determine the extent of salinity. Also, the electrical conductivity (EC) of the soil can be helpful for the classification of the land. Based upon CRSI values, the chemical analysis of randomly sampled farmland soils could provide a more detailed analysis of salt species concentration, which would be useful in distinguishing between anthropogenic or natural salinity.

5.3 The Direct Site Observations

The on-site visit by the UND research team helped in making first-hand visual observations related to corroded pipelines, leaking aging oil well infrastructures and correlating with the reported findings in the thesis. As it was observed by the UND team, an unattended oil exploration facilities had a much higher probability of leaking saline pungent dirty water stream with the pungent sulfur smell into adjacent farmlands. It is likely that such conditions occurring near the injection well sites may have health issue due to poorly maintained living conditions for the residents as was observed during a team visit. The visited farmland sites adjacent to the oil well exploration facilities where brine spills have been frequently reported have shown CRSI values less than 0.6 with stressed vegetation and salt tolerant plants growing with no sign of the restoration of farming of former buzzing lush greens farmlands. This area is a very sparsely populated with mostly farmland and oil wells as the primary economic resources. Many of farmers in this region are generational farmers with having a good know-how of farming as their profession, some farmers lease farmland and some own the farmlands. Most farmers in these areas want to keep alive the family tradition of farming practices for their livelihood means. As per the host farmers in the study areas, they have seen a gradual decrease in their farming produce due to brine spills contamination in their respective farmlands which have impacted their livelihood with loss of business (Figures 4.1-4.4). Local surrounding communities have expressed that the brine contaminants have polluted the local environment, reservoirs, streams, local forestation, aquatic resources of these areas and wetlands in river streams. Geologists, scientists, geographers, and local environmentalists have expressed severe concerns because of pollution created by oil well exploration activities and brine spills.

5.4 Final Remarks

The remote sensing method incorporated with CRSI salinity index has excellent potential to identify brine spill locations where the oil well exploration facilities as this method is a proven least error method which can be effectively used to understand soil salinity issues and thus can help with precision farming, deforestation, wetland and aquatic resources (Scudiero, Skaggs and Corwin 2015) . However, the main drawback is that the NDDH website data reported that Incident ID forms are not accurately presented in terms of exact brine spills coordinates, but the data has been reported direction based "quarter", or "quarter-quarter" sections which suggest the possible areas of brine and crude spills range between 0.66 million m^2 (162 acres) to 0.16 million m^2 (40 acres) of the span. This direction based Incident ID reports locations spanning 0.66 million m^2 (162 acres) create data error in terms of exact location spills. That is why exact geological coordinates based data reporting system with detailed brine, crude and "other" spills with " no blank " data reporting style is essential in order to get the error free CRSI values. Also, to understand the more in-depth trend analysis, instead of one month, all harvesting seasons data from all several months would provide better CRSI value-based analysis. However, despite all these issues, upon comparisons, the CRSI salinity index method can be one of the essential tools to analyze soil salinity in farmlands and thus can be an excellent help for precision farming, vegetation, forestation, wetlands protection.

5.5 Future Research

The June month was chosen for this analysis since it can give a better analysis of the farmlands as the cloud covers are relatively low compared to the later months of mid-July, August and September. Also, May and June's months are the beginning of the growing season so farmers try to remediate and reclaim the soil which can give the better assessment of the farmland with the least error. However, adding entire growing season months from May to September would give a much better analysis in terms of salinity impacts with respect to time. Also, the detailed brine and crude spill data to identify periods before and after major spills in terms of other remote sensing technologies and more months and years inclusion would help solve the existing problem. Analysis of Landsat scenes over multiple years to better identify changes to CRSI values over time and on that basis, the ground soil samples collection and lab analysis for EC (Electrical Conductivity) would determine the facts in a more precise way and thus can help spectral signature for such salinity issues.

References

Allbed, A., Kumar, L. 2013.*Soil Salinity Mapping and Monitoring in Arid and Semi-Arid Regions Using Remote Sensing Technology*. A Review, Advances in Remote Sensing, 2013, 2, 373-385., http://file.scirp.org/pdf/ARS_2013122611191714.pdf

Alley, W. M., 1984. *The Palmer Drought Severity Index: Limitations and Assumptions.* Journal of Climate and Applied Meteorology, Vol. 23, U.S.Geological Survey, Reston, VA 22092.

Alley, W. M., 1985. *The Palmer Drought Severity Index As a Measure Of Hydrologic Drought*, Water Resources Bulletin American, Water Resources Association Vol. 21, No. 1.

ArcGIS, ESRI, Redland, CA, USA. Website: https://www.esri.com/en-us/arcgis/products/arcgis-online/overview (accessed September 20, 2016).

Beal, W.A., Murphy, E.C., and Kehew, A.E.1987.*Migration of contaminants from buried oil-and-gas drilling fluids within the glacial sediments of north-central North Dakota.* North Dakota Geological Survey, Report of Investigation 86, 43 p.

Bluemle J.P., 1985. *NDGS Newsletter June 1985.*North Dakota Geological Survey, Grand Forks, ND.

Bluemle J.P., 2000. *The Face of North Dakota*. Bismarck, N.D: North Dakota Geological Survey.

Bluemle J.P., 2001.*The 50th Anniversary of the Discovery of Oil in North Dakota.* Miscellaneous Series No. 89 North Dakota Geological Survey.

Butchireddygari, L., 2018. *Salting the earth: North Dakota farmers struggle with a toxic byproduct of the oil boom*. U.S.News, https://www.nbcnews.com/news/us-news/salting-earth-north-dakota-farmers-struggle-toxic-byproduct-oil-boom-n895771

Chaturvedi, L., K. R. Carver, G. D. Hancock, F. V. Small, J. C. Harlan, and K. J. Dalstead. 1983. *Multispectral Remote Sensing of Saline Seeps*. IEEE Transactions on Geoscience and Remote Sensing GE-21:239-251.

Dalrymple, A., *2014.Landowners say ND oil patch protections 'failing miserably'*. Prairie Business, https://www.prairiebusinessmagazine.com/business/3969445-landowners-say-nd-oil-patch-protections-failing-miserably

Dalrymple, A., 2018.*Company faces fine for failing to report ND oilfield spill*, Bismarck Tribune Website: https://www.thedickinsonpress.com/news/4403223-company-faces-fine-failing-report-nd-oilfield-spill

Doll et al. 1985. Doll, E. C., Foss J. E., McCarthy G. J., and Murphy E. C. 1985. *Characterization of Detrimental Effects of Salts and Other Chemical Constituents Carried in Surface and Subsurface Waters from Brine and Drilling Fluid Disposal Pits Buried During Oil*

Development. Fargo, North Dakota. Land Reclamation Research Center, North Dakota State University.

Doll, E.C., 1989. *Chemical analysis of soils contaminated with oilfield brine: Mandan, N.D.*, North Dakota State University, Land Reclamation Research Center Bulletin No. 521, p. 9.

Dresel E. P. and Rose A.W., 2010. *Chemistry and Origin of Oil and Gas Well Brines in Western Pennsylvania* (open – file oil and gas report 10-01.0) (accessed December 9, 2017).

Dwivedi, R. S., Rao B. R. M., 1992. *The Selection of the Best Possible Landsat TM Band Combination for Delineating Salt-Affected Soils*. International Journal of Remote Sensing Vol. 13, Iss. 11, 2015-2058.

Earth Point Tools for Google Earth, 2017. Website: http://www.earthpoint.us/, Boise, USA, 2017 (accessed December 9, 2017)

Energy Environmental Research Center (EERC) and North Dakota State University (NDSU). 2016. *North Dakota Remediation Resource Manual.* Grand Forks, North Dakota, (accessed December 9, 2017).

Energy Environmental Research Center (EERC). 2015. *Liquids Gathering Pipelines: A Comprehensive Analysis.* Grand Forks, North Dakota: Energy and Environmental Research Center, University of North Dakota, (accessed December 9, 2017)

Fan, X., B. Pedroli, G. Liu, Q. Liu, H. Liu, and L. Shu. 2012. *Soil salinity development in the yellow river delta in relation to groundwater dynamics.* Land Degradation and Development 23:175-189.

Farifteh, J., A. Farshad, and R. J. George. 2006. *Assessing salt-affected soils using remote sensing, solute modeling, and geophysics.* Geoderma 130:191-206.

Ferrar, K., MPH' By Munster K. and Ferrar K., 2017. *Oil Spills in North Dakota: What does DAPL mean for North Dakota's future?* Western Program Coordinator, FracTracker Alliance. April 11, 2017, Article.

Food and Agricultural Organization of the United Nations FAO, 2018., http://www.fao.org/docrep/x5871e/x5871e04.htm (accessed December 9, 2017)

Gleason R.A., Thamke J.N., Smith B.D., Tangen B.A., Chesley-Preson T, Preston T.M. 2011. *Examination of Brine Contamination Risk to Aquatic Resources from Petroleum Development in the Williston Basin* USGS Report, Fact Sheet 2011-3047.

Gleason, R.A., and Tangen, B.A., eds., 2014. Brine contamination to aquatic resources from oil and gas development in the Williston Basin, United States: U.S. Geological Survey Scientific Investigations Report 2014–5017, 127 p., http://dx.doi.org/10.3133/sir20145017

Gottesdiener, L., 2014. *In the shadow of the oil boom, North Dakota farmers Fight contamination, Al Jazeera America*, http://america.aljazeera.com/articles/2014/9/6/north-dakota-wastewaterlegacy.html

Haines S.S.,Jenni K.E., Nieman T.L., P.E. Zell, van der Burg M.P.,Preston M.T., Smith B.D., Tangen B.A., and Thamke J.N. 2014.*Brine Contamination to Aquatic Resources from Oil and*

Gas Development in the Williston Basin. The United States, Technical Report · June 2014, DOI: 10.3133/sir20145017.

Hansen et al. 2006. Hansen, J., M., Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, 2006: *Global temperature change*. Proc. Natl. Acad. Sci., 103, 14288-14293.

Hansen, J., 2006: *The threat to the planet*. New York Rev. Books, 53, no. 12, 12-16.

Headwaters Economics. 2014. *How North Dakota Returns Unconventional Oil Revenue to Local Governments* Website: https://headwaterseconomics.org/wp-content/uploads/state-energy-policies-nd.pdf (accessed December 17, 2017).

Hem, J.D.1985.*Research and Interpretation of the Chemical Characteristics of Natural Water.* 3rd Edition, US Geological Survey Water Supply Paper 2254, 1-263.

Hick, P.T., and Russell, W.G.R. (1990). "Some spectral considerations for remote sensing of soil salinity." Australian Journal of Soil Research, 28, 417–431

Hillel, D., 2000. *Salinity Management for Sustainable Irrigation: Integrating Science, Environment, and Economics,* World Bank Publications, Washington DC, 2000. http://dx.doi.org/10.1596/0-8213-4773-X, Accessed on 12/9/2016.

Huete R., 1988. *A Soil-Adjusted Vegetation Index (SAVI),* Remote Sensing of Environment, Vol. 25, No. 3, 1988, pp. 295-309.

Iampen, H. T. and Rostron, B. J., 2000. *Hydrogeochemistry of pre-Mississippian brines, Williston Basin, Canada-USA.* Journal of Geochemical Exploration - J GEOCHEM EXPLOR. 69. 10.1016/S0375-6742(00)00007-8.

Ibrahim, H. A. M. 1987.*Delineation and mapping of saline soils and moving sands in NE Egypt from Landsat MSS data. Advances in digital image processing.* Proc.RSS 13th annual conference, Nottingham, 1987, (Remote Sensing Society, University of Nottingham) 470-477.

Kalkhoff SJ, 1993, *Using a Geographic Information System to Determine the Relation Between Stream Quality and Geology in the Roberts Creek Watershed, Clayton County, Iowa. Supervisory Hydrologist,* U.S. Geological Survey http://onlinelibrary.wiley.com/doi/10.1111/j.1752-1688.1993.tb03261.x/abstract;jsessionid=1D59CDCA07003CF835601F559C39A308.f02t02

L3Harris Geospatial Solutions, Broomfield, CO, USA. Website: https://www.harrisgeospatial.com/Company/Careers (accessed on September 26, 2017).

Lauchi A. and Grattan, S.R. 2007a. Plant *Growth and Development and Development Under Salinity Stress,* Department of Land, Air and Water Resources, University of California. Springer

Läuchli A, and Grattan S. R. 2012a. *Soil pH extremes.* In. S. Shabala (ed) .Plant Stress Physiology.CAB International.pp 194–209.

Läuchli A, and Grattan S. R. 2012b. *Plant responses to saline and sodic conditions.* In. (W.W. Wallender and K.K. Tanji, eds). Agricultural Salinity Assessment and Management (2nd edition). ASCE pp 169–205.

Läuchli A. and Grattan S. R. 2007b. *Agricultural Salinity Assessment, and Management*, University of California.

Lauer, N. E., Harkness J. S., and Vengosh A. 2016. *Brine Spills Associated with Unconventional Oil Development in North Dakota.* Environmental Science and Technology 50:5389-5397.

LeFever J. and LeFever R., 2005. *Salts in Williston Basin, North Dakota.* North Dakota Geological Survey (NDGS) Report, North Dakota Geological Survey, University Station, Grand Forks ND 58202 and Department of Geology and Geological Engineering University of North Dakota Grand Forks ND 58202. Website: https://www.dmr.nd.gov/ndgs/documents/Publication_List/pdf/RISERIES/RI-103.pdf (accessed December 7, 2017).

Leskiw et al., 2012. Leskiw L.A., Sedro R.B., Welsh C.M., Zeleke T.B. 2012 *Soil and vegetation recovery after a good blowout and saltwater release in northeastern British Columbia*, Can. J. Soil Sci., 92 , pp. 179–190

Manly Bryan F. J.2008. *Statistics For Environmental Science and Management*, 2nd Edition

Meehan, Miranda & Sedivec, K & DeSutter, Tom & Augustin, Chris & Daigh, Aaron. 2017. *Environmental impacts of brine (produced water)*. North Dakota State University Extension Service Pub. R1850.

Merrill, S.D., K.J. Lang, E.C. Doll, *Contamination of soil with oil-field brine and reclamation with calcium-chloride,* Soil Sci., 150 (1990), pp. 469–475, (USGS, Scientific Investigations Report 2014–501).

Murphy, E.C., 1983.*The effect of oil and gas well drilling on shallow groundwater in western North Dakota.* The University of North Dakota, Master's Thesis, 242 p.

Murphy, E.C., and Kehew, A.E., 1984.*The effect of oil and gas well drilling fluids on shallow groundwater in western North Dakota.* North Dakota Geological Survey Report of Investigation No. 82, 156 p.

Murphy, E.C., Kehew, A.E., Groenewold, G.E., and Beal, W.A., 1988.*Leachate generated by an oil-and-gas brine pond site in North Dakota*. Ground Water, v. 26, p. 31–38.

Murphy E., 2014. Reserve Pit and   Brine Pond Studies in North Dakota. Presented to the Energy Development and Transmission Committee Senator Rich Wardner, Chair Minot, ND April 8, 2014, North Dakota Geological Survey Geologic Investigations No. 175

National Center for Atmospheric Research (NCAR) 2018. *Climate Data Guide. Website:* https://climatedataguide.ucar.edu/climate-data/palmer-drought-severity-index-pdsi (accessed December 12, 2018)

National Oceanic and Atmospheric Administration (NOAA) 2017. National Environmental Satellite, Data, and Information Services, Website: https://www7.ncdc.noaa.gov/CDO/CDODivisionalSelect.jsp (accessed December 9, 2017)

Natural Resources Conservation Service (NRCS), 2017. North Dakota, United States Department of Agriculture, Website: https://www.nrcs.usda.gov/wps/portal/nrcs/site/nd/home/, (accessed December 9, 2017).

North Dakota Century Code 2013, Title 38—*Mining and gas and oil production*, Website: http://www.legis.nd.gov/cencode/t38.html (accessed July 1, 2017)

North Dakota Department of Health (NDDH). 2017. *Environmental incident reports. Oilfield environmental incidents.* Available online at https://deq.nd.gov/FOIA/Spills/defaultarc.aspx/ (accessed December 12, 2017)

North Dakota Geological Survey (NDGS).2017. *Overview of the Petroleum Geology of the North Dakota Williston Basin.* Website: https://www.dmr.nd.gov/ndgs/resources/, (accessed on December 9, 2017).

North Dakota GIS Hub Data Portal (ND GIS Hub Data Portal).2017. *Department of Environmental Quality*. 2017. Website : https://gishubdata.nd.gov/search/field_topic/environment-39 (accessed December 9, 2017)

North Dakota of Oil and Gas Division (ND Oil and Gas Division). 2017. *Monthly Oil and Gas Production*. Website: https://www.dmr.nd.gov/oilgas/ (accessed December 9, 2017).

North Dakota Oil and Gas Division (ND Oil and Gas Division). 2013. *Rules and regulations,* https://www.dmr.nd.gov/ oil gas/rules/rulebook.pdf. (accessed March 2017)

North Dakota Studies (ND Studies) 2018. *Energy: Powered by North Dakota*. 2018. Website: https://www.ndstudies.gov/energy/level2/ (accessed March 18, 2018)

Peterman, Z. E., Thamke, J. N., Futaa, K., and Preston, T. M., 2012. *Strontium isotope systematics of mixing groundwater and oil-field brine at Goose Lake in northeastern Montana, USA.* Applies Geochemistry, 27 (2012) 2403-2408.

Pollastro R. M., Roberts L.N.R., and Cook T. A., 2013. *Geologic Assessment of Technically Recoverable Oil in the Devonian and Mississippian Bakken Formation*

Preston T.M., Chesley-Preston T.L., 2015, *Risk assessment of brine contamination to aquatic resources from energy development in glacial drift deposits: Williston Basin, USA,* Science of the total environment. https://doi.org/10.1016/j.scitotenv.2014.11.054

Preston, T. M., T. L. Chesley-Preston, and J. N. Thamke. 2014. *A GIS-based vulnerability assessment of brine contamination to aquatic resources from oil and gas development in eastern Sheridan County, Montana.* Science of the Total Environment 472:1152-1162.

Quirk, J. P., 2001.*The Significance of the Threshold and Turbidity Concentrations in Relation to Sodicity and Microstructure.* Australian Journal of Soil Research 39(6) 1185 – 1217.

Reiten, J.C., and Tischmak, T., 1993.*Appraisal of oil field brine contamination in shallow ground water and surface water, eastern Sheridan County, Montana. Billings,* Mont., Montana Bureau of Mines and Geology Open-File 260, 296 p., 2 sheets.

Richards L.A., ed. 1954. *Diagnosis and Improvement of Saline and Alkali Soils.* Agriculture Handbook No. 60 Issued February 1954 United States Department of Agriculture; U.S. Salinity Laboratory Staff; U.S. Dept. of Agriculture (USDA), Washington, D.C., rev. ed., 1954. Vii + 160 pp. (accessed December 12, 2017).

Robbins, C.W., and Wiegand, C.L.1990.*Field and laboratory measurement.* In: Tanji, K.K., (ed.) Agricultural Salinity Assessment and Management. ASCE Manual, No. 71. pp. 203-219. ASCE. https://eprints.nwisrl.ars.usda.gov/id/eprint/804

Rouse, D.R., Nelson, K.J., and Reiten, J.C., 2013, *Impacts of oil exploration and production to the Northeast Montana Wetland Management District: Montana Bureau of Mines and Geology* Open-File Report 620, 264 p., 1 sheet. Website: http://www.mbmg.mtech.edu/mbmgcat/public/ List Citation.asp?pub_id=31635&.) (accessed December 12, 2017).

Rundquist, B., and Vandeberg, G., 2013. *Fully engaging students in the remote sensing process through field experience*, Journal of Geography. 112 (6):262-270. 2013. DOI:10.1080/00221341.2013.765902.

Scudiero, E., Skaggs T.H., and Corwin D.L., 2015. *Regional-scale soil salinity assessment using Landsat ETM+ canopy reflectance.* Remote Sensing of Environment 169:335-343.

Scudiero et al. 2017, Scudiero E, Corwin D, Anderson R, Yemoto K, Clary W, Wang Z, Skaggs T. 2017. *Remote sensing is a viable tool for mapping soil salinity in agricultural lands.* California Agriculture; 71(4):231-238. Research article, Website: https://doi.org/10.3733/ca.2017a0009.

Seelig B.D., 2000.*Salinity and Sodicity in North Dakota Soils*. NDSU Extension Service. North Dakota State University.

Shainberg I., Singer, M. J., 2011.*Agricultural Salinity Assessment and Management Chapter 5: Soil Response to Saline and Soil Conditions*, page 139. Published online by American Society of Civil Engineers.

Shrestha, D. P., and A. Farshad, Chapter 13. *Mapping Salinity Hazard: An Integrated Application of Remote Sensing and Modeling-Based Techniques* In G. Metternicht and J. A. Zinck, Eds., Remote Sensing of Soil Salinization: Impact on Land Management, CRC Press, Boca Raton, 2008, p. 257. http://www.scirp.org/reference/ReferencesPapers.aspx?ReferenceID=1046634

Shrivastava P. and Kumar R. 2014.Soil salinity: *A serious environmental issue and plant growth promoting bacteria as one of the tools for its alleviation.* Saudi Journal of Bioscience.

Springer. P., 2018.*80 percent of ND oil spills would not have been reported under the new law*, Grand Forks Herald, Website: https://www.grandforksherald.com/news/government-and-politics/4426763-80-percent-nd-oil-spills-wouldnt-have-been-reported-under-new

Thamke, J.N., and Craigg, S.D., 1997, *Saline-water contamination in Quaternary deposits and the Poplar River, East Poplar oil field, northeastern Montana*: U.S. Geological Survey Water-Resources Investigations Report 97–4000, 37 p.

United States Environmental Protection Agency (EPA). 1977. The report to Congress; *waste disposal practices and their effects on ground water*. EPA-570/9-77-002

United States Environmental Protection Agency (EPA). 1999. Underground Injection Control (UIC) EPA, 1999. Website: https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells (accessed December 9, 2017)

United States Geological Survey Department of the Interior (USGS). 2013. *Assessment of Undiscovered oil resources in the Bakken and Three Forks Formations, Williston Basin Province, Montana, North Dakota, and South Dakota*. Website: http://pubs.usgs.gov/fs/2013/3013/fs2013-3013.pdf (accessed December 12, 2017).

United States Energy Information Administration (EIA). 2018. *North Dakota state energy Profile*. Website: https://www.eia.gov/state/?sid=ND (accessed January 10, 2019).

United States Geological Survey (USGS). 2017. *Landsat Missions*. Website: https://www.usgs.gov/land-resources/nli/landsat (accessed on December 18, 2017).

VanderBusch C., 2017. *Abandoned Well Plugging and Site Restoration Fund "AWPSRF",* North Dakota's AWPSRF Program, Department of Mineral Resource, North Dakota. Website: http://ndreclamation.com/wp-content/uploads/2017/02/05-VanderBusch-022017.pdf (accessed December 12, 2017).

Zhang, T., Qi, J., Gao, Y., Ouyang, Z., Zeng, S., & Zhao, B. 2015. *Detecting soil salinity with MODIS time series VI data.* Ecological Indicators, 52, 480–489.

Zhang, T., Zeng, S., Gao, Y., Ouyang, Z., Li, B., Fang, C., et al., 2011. *Using hyperspectral vegetation indices as a proxy to monitor soil salinity.* Ecological Indicators, 11, 1552–1562.

Appendix: A

CRSI Images

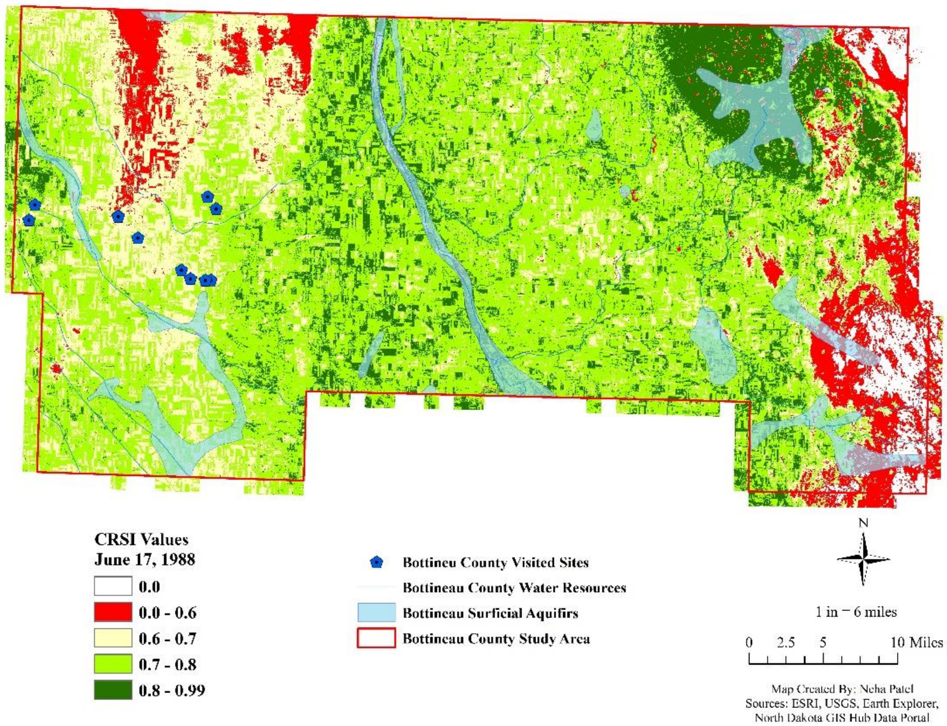

Figure A- 1: Bottineau County CRSI Value on June 17, 1988.

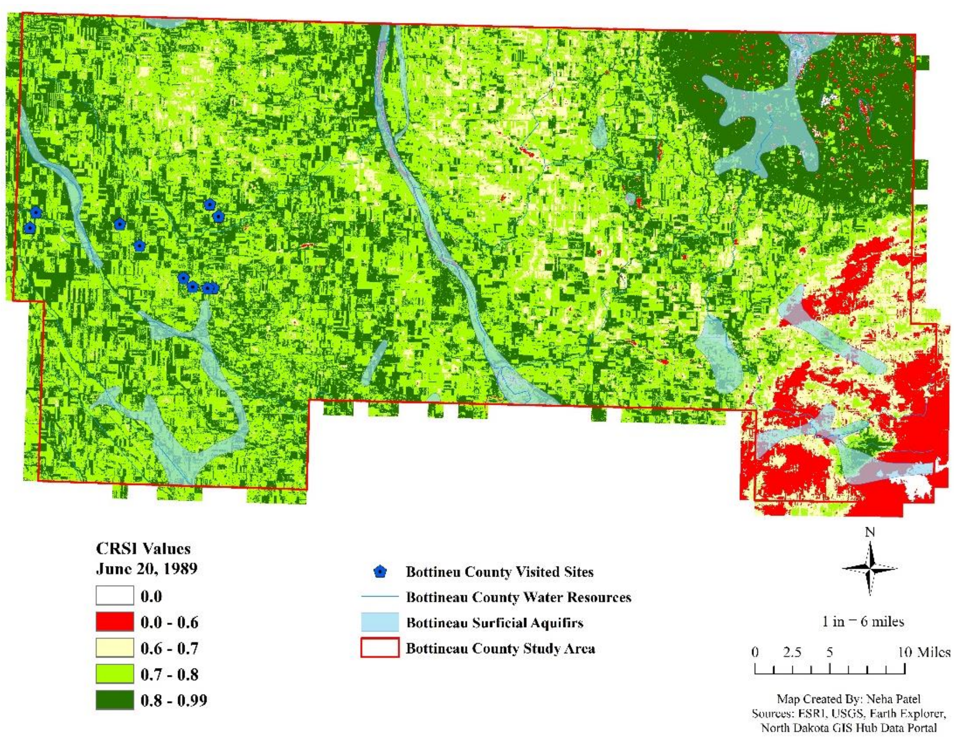

Figure A-2: Bottineau County CRSI Value on June 20, 1989.

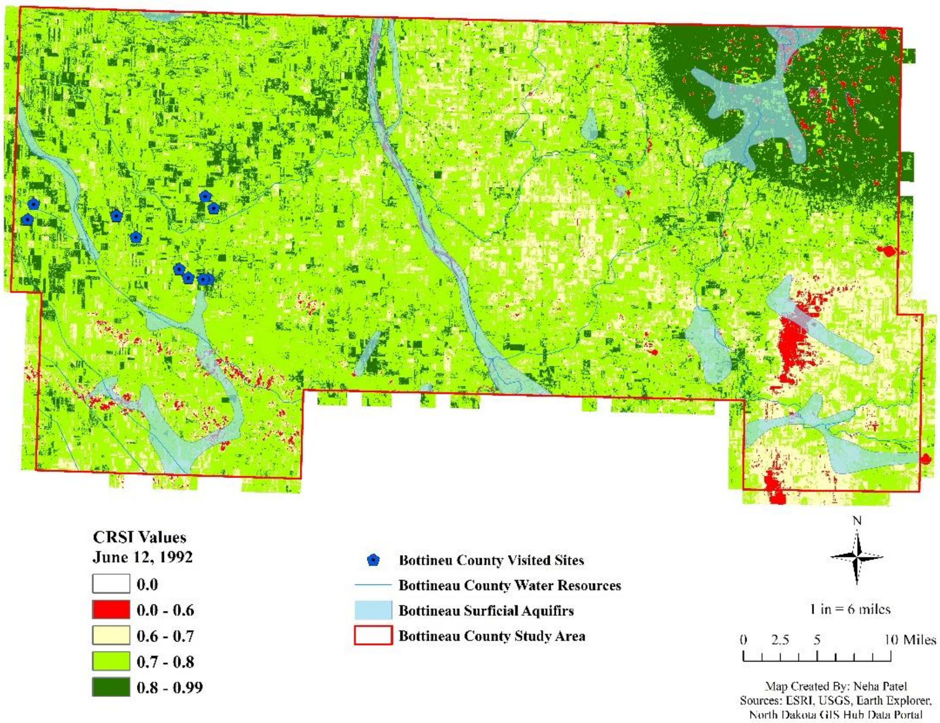

Figure A-3: Bottineau County CRSI Value on June 12, 1992.

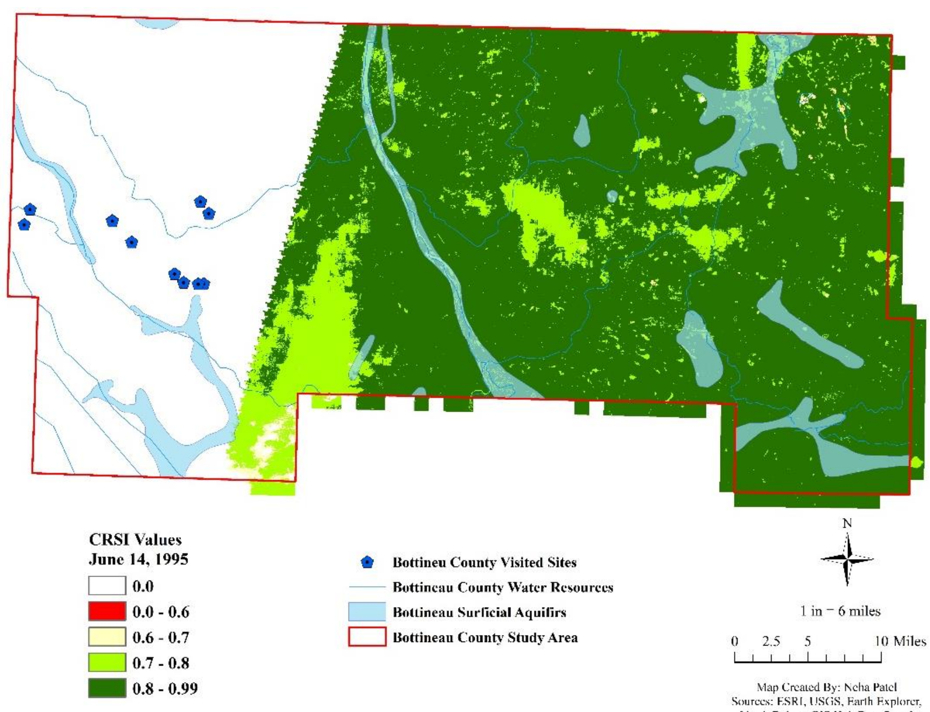

Figure A- 2: Bottineau County CRSI Value on June 14, 1995.

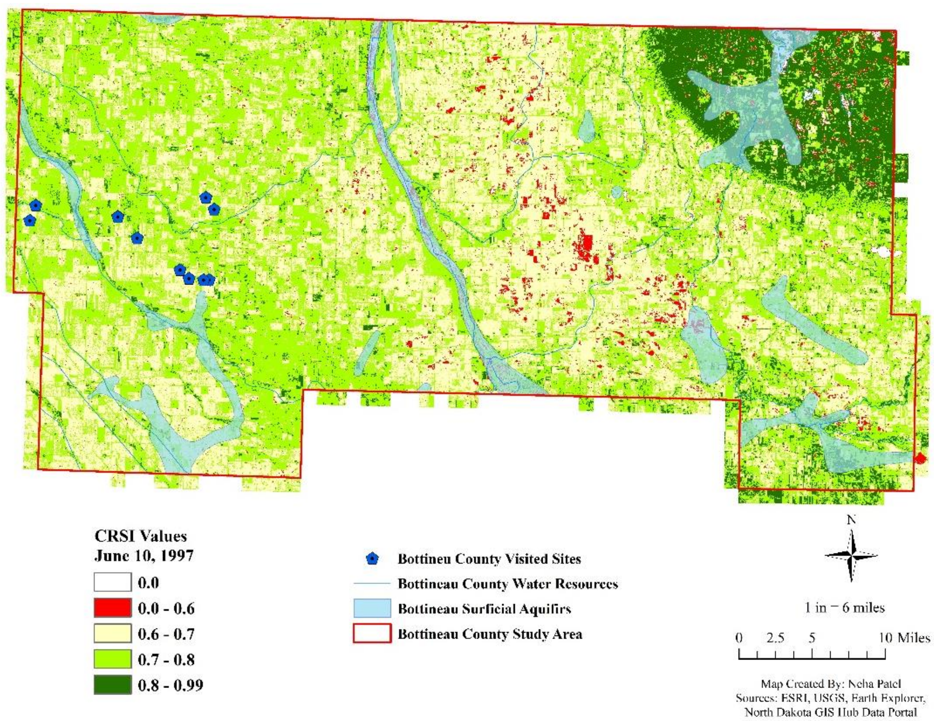

Figure A- 3: Bottineau County CRSI Value on June 10, 1997.

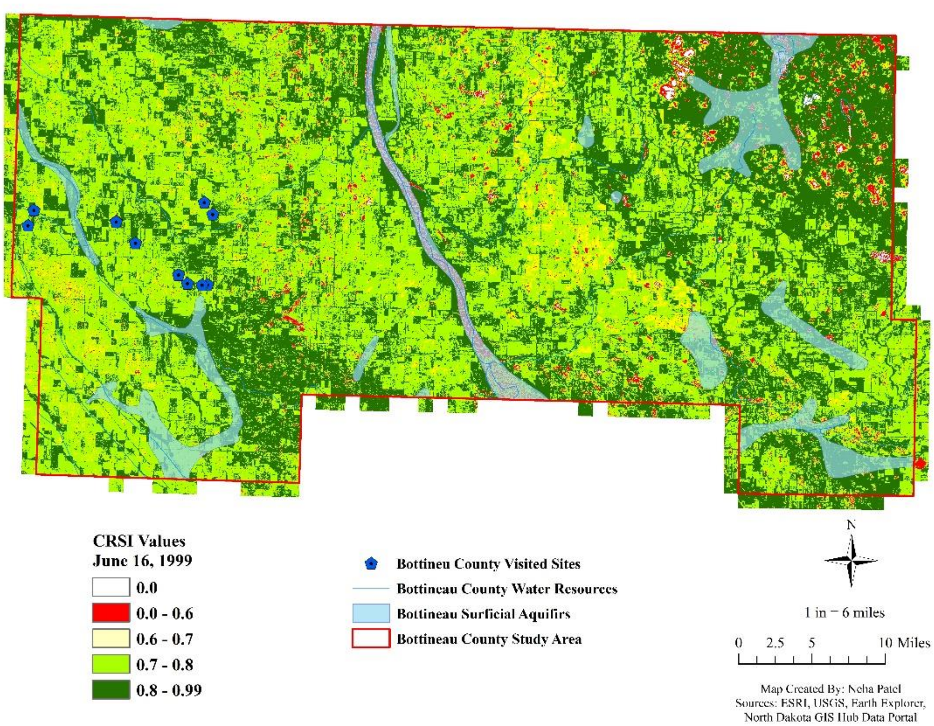

Figure A- 4: Bottineau County CRSI Value on June 16, 1999.

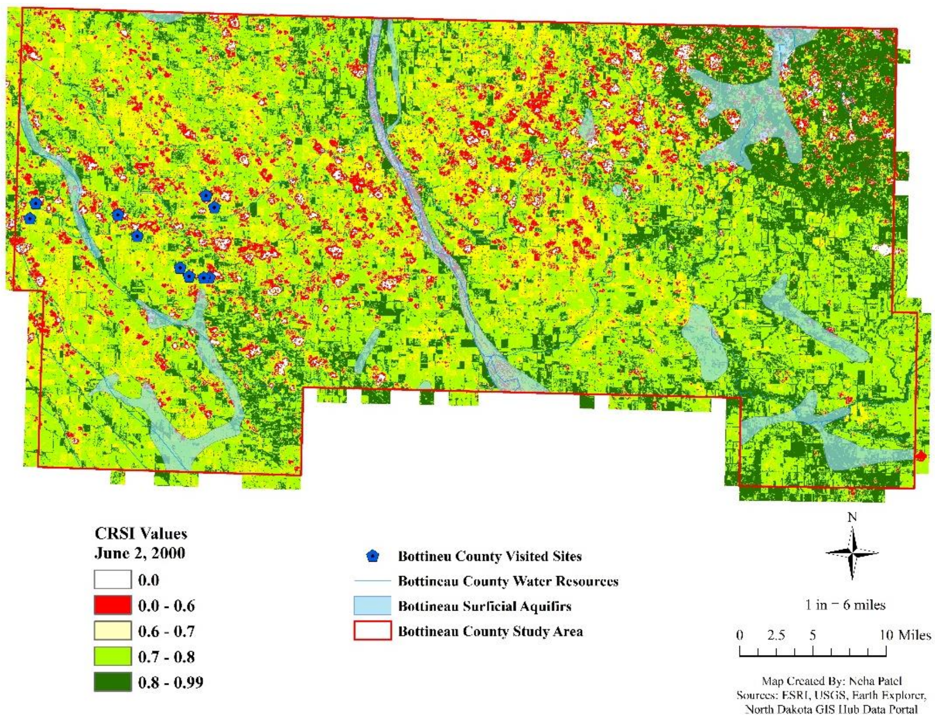

Figure A- 5: Bottineau County CRSI Value on June 02, 2000.

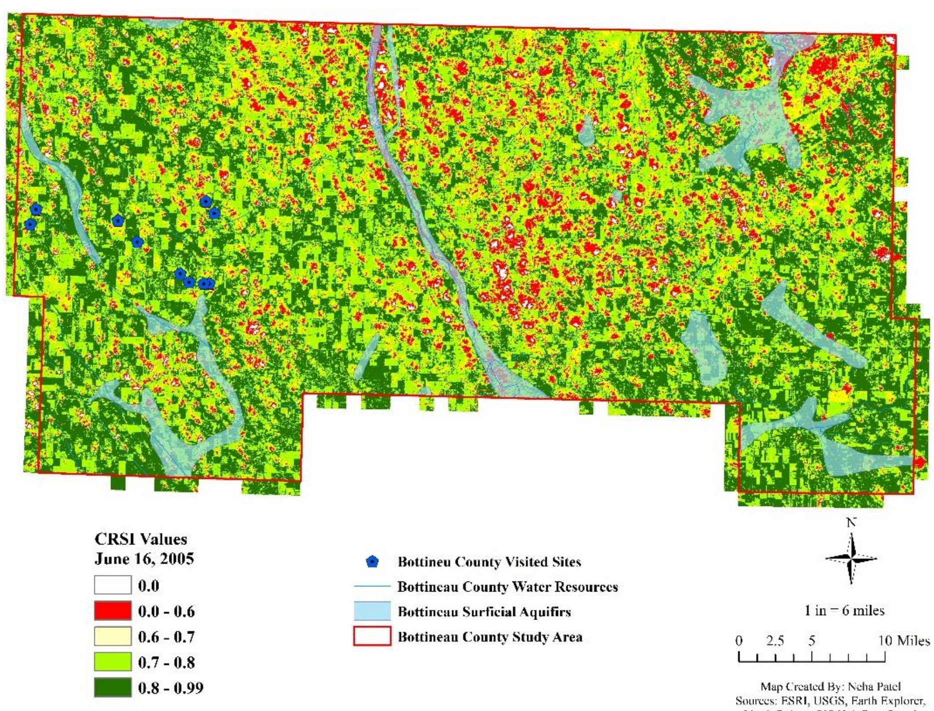

Figure A- 6: Bottineau County CRSI Value on June 16, 2005

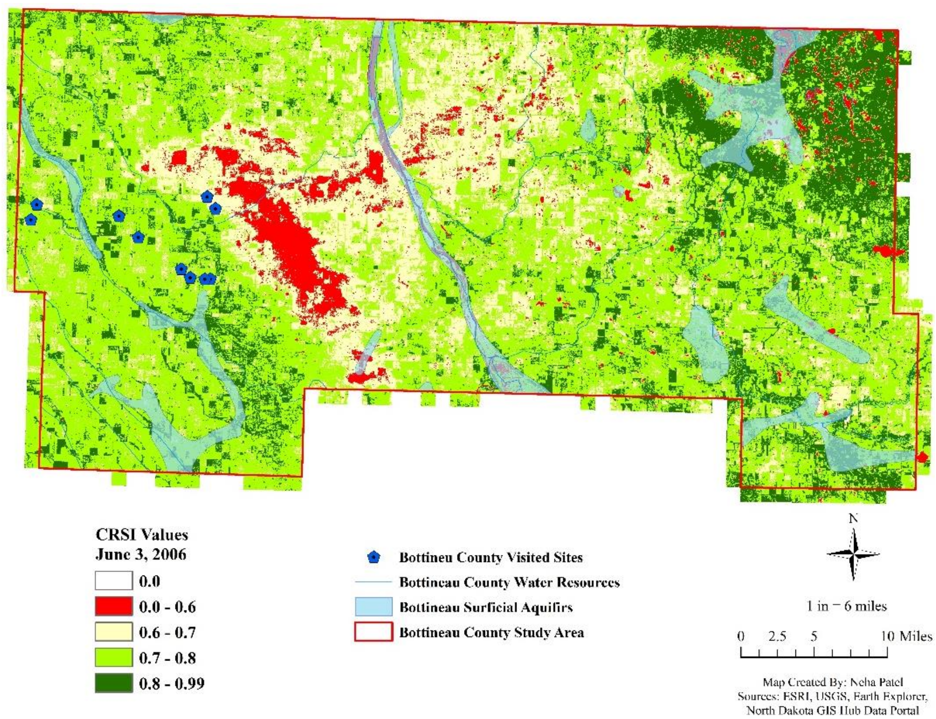

Figure A- 7: Bottineau County CRSI Value on June 03, 2006.

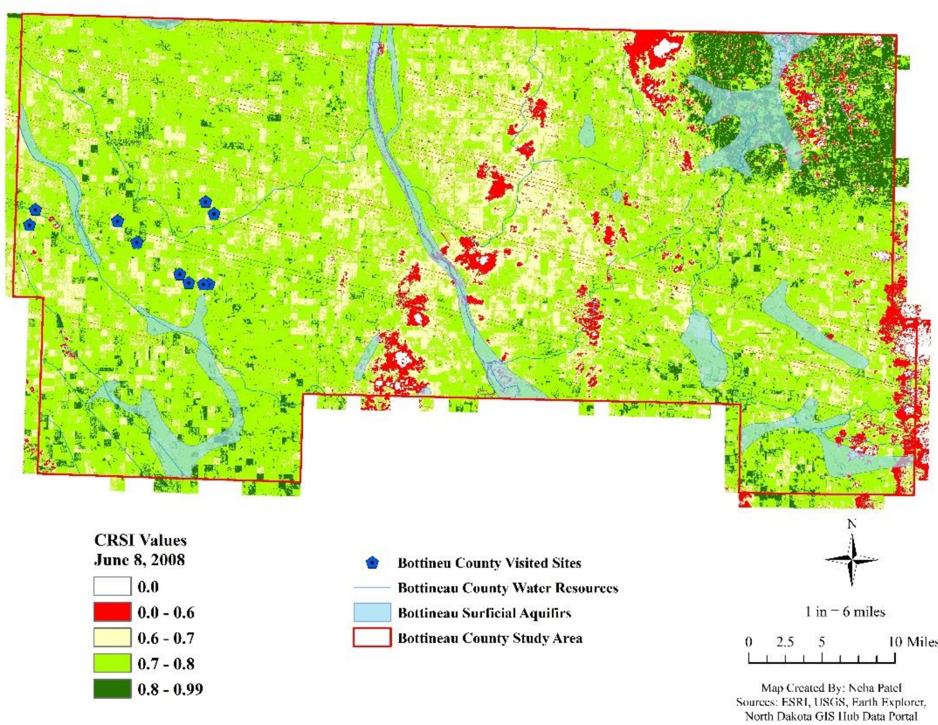

Figure A- 8: Bottineau County CRSI Value on June 08, 2008.

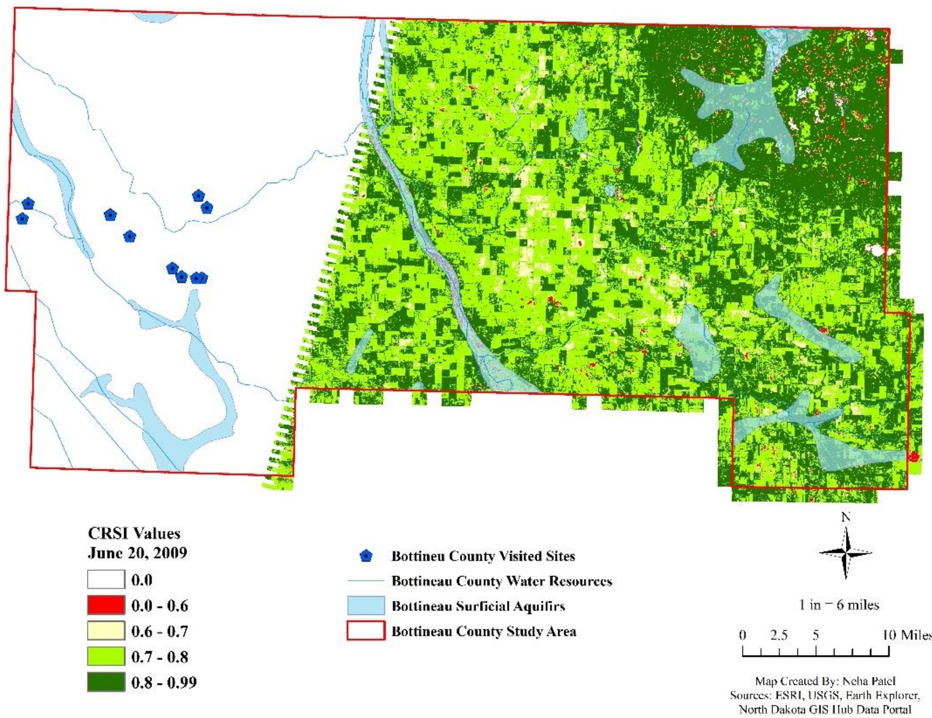

Figure A- 9: Bottineau County CRSI Value on June 20, 2009.

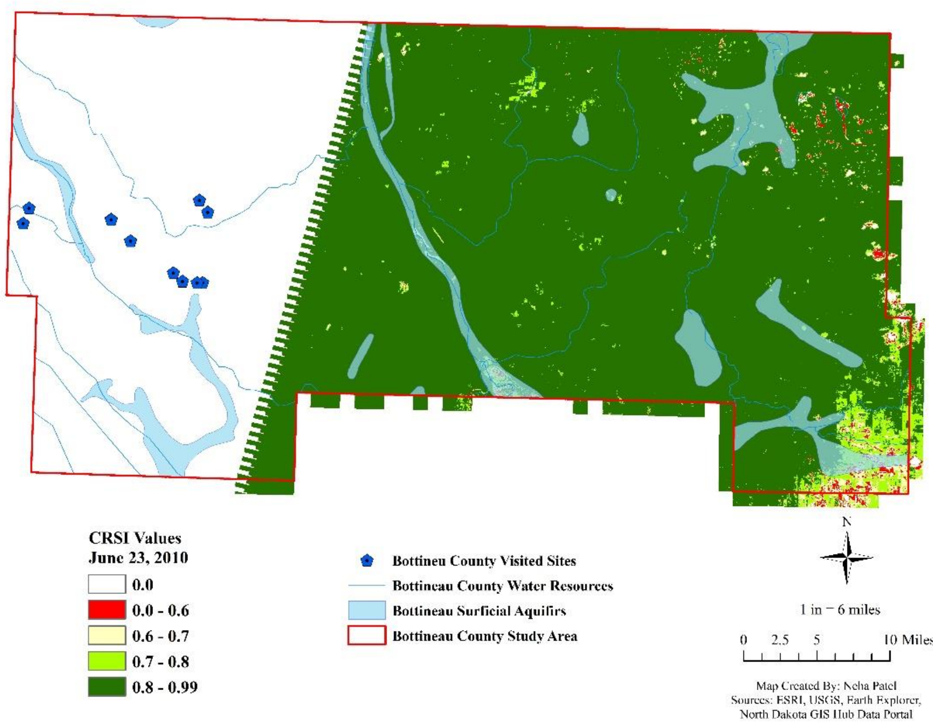

Figure A- 10: Bottineau County CRSI Value on June 23, 2010.

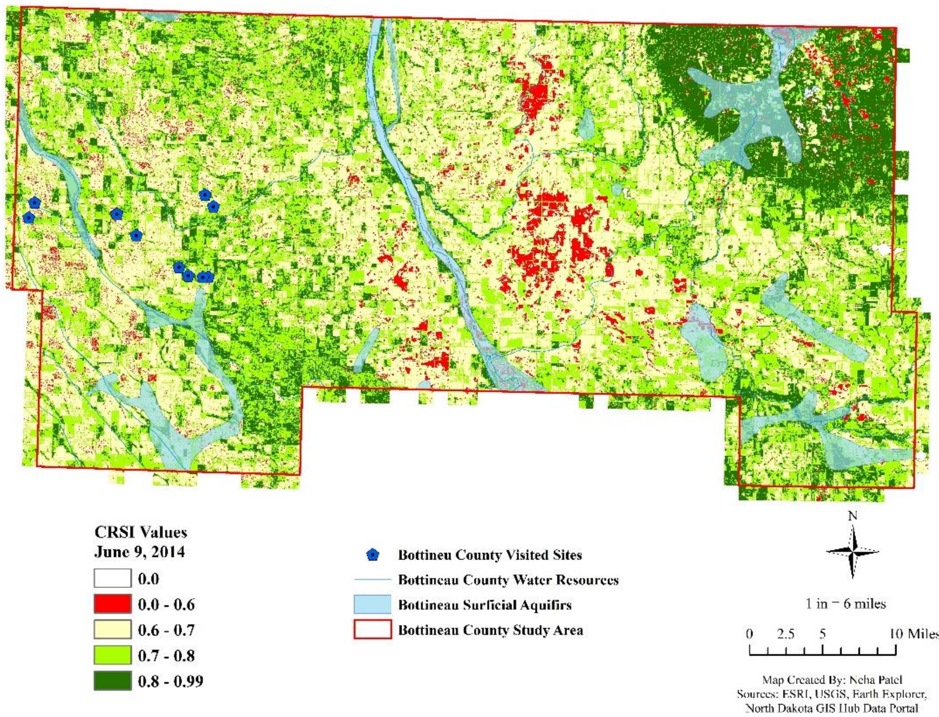

Figure A- 11: Bottineau County CRSI Value on June 09, 2014.

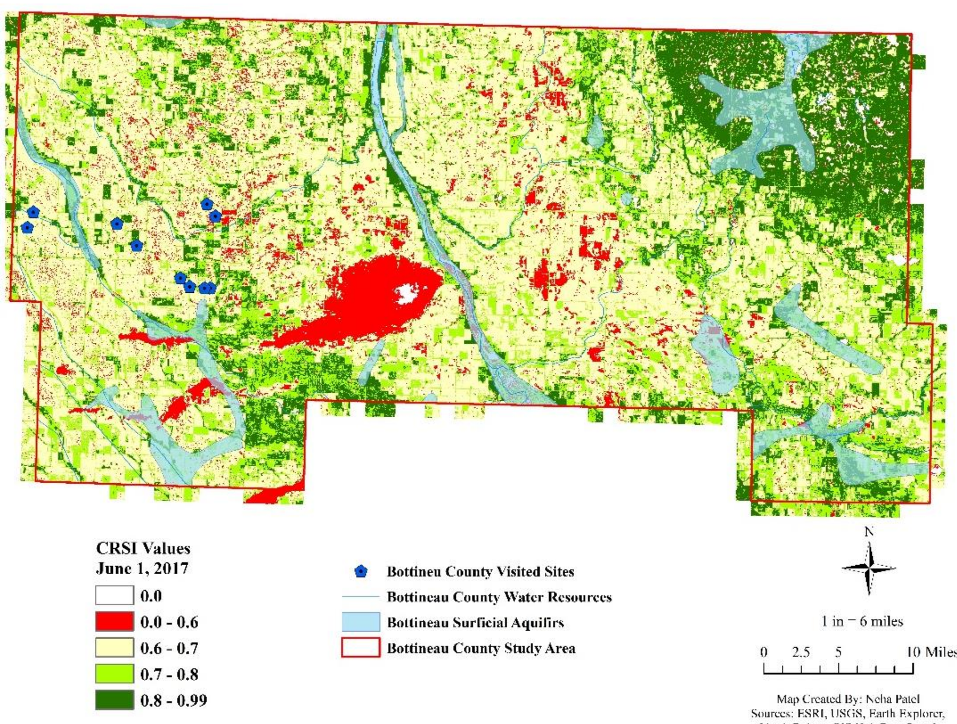

Figure A- 12: Bottineau County CRSI Value on June 01, 2017

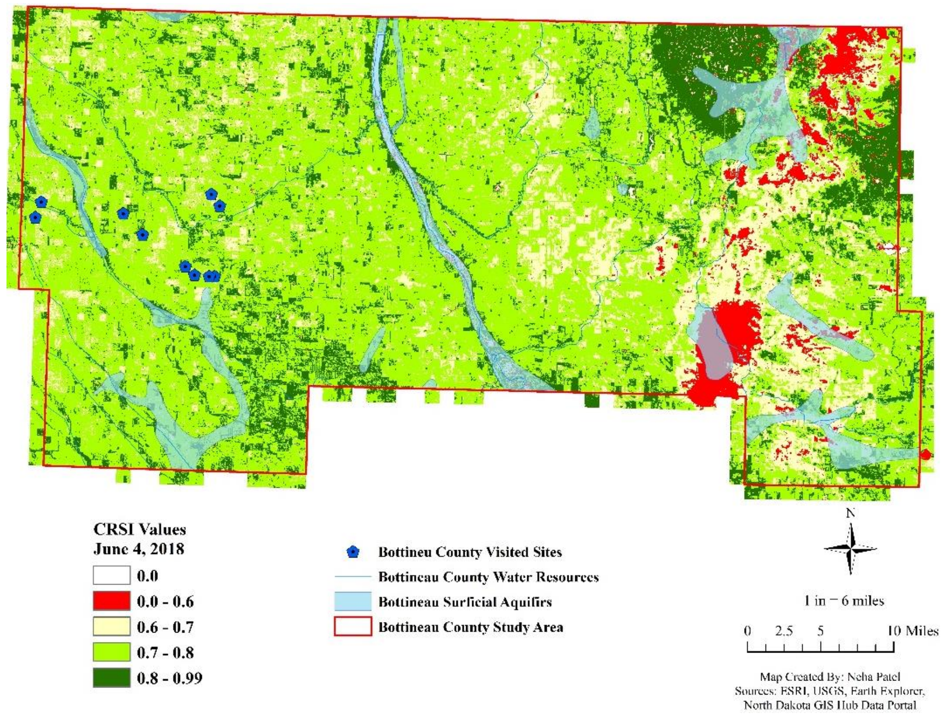

Figure A- 13: Bottineau County CRSI Value on June 04, 2018.

Appendix: B

Oil Well Information

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Township Range Sections	Salt Water	Oil Volume
Nelson #2-13 SWD	2554	20-Sep-04	NDT159NR82WSec13	2100	0.00
TRENDSKAADEN 44-282	20110803100400	21-Jul-11	NDT163NR77WSec28	1500	0.00
RICE-STATE 2H	20120626171300	26-Jun-12	NDT161NR82WSec16	800	0.00
Haugen BCTB	20140606093900	6-Jun-14	NDT161NR82WSec25	700	0.00
Madsen CTB	20111201132200	19-Nov-11	NDT163NR77WSec28	700	0.00
Wilms Injection Plant (Wilms)	2362	6-Jan-04	NDT161NR82WSec23	650	0.00
CRAMER1SWD	20121027080900	26-Oct-12	NDT161NR82WSec8	600	0.00
	1994	29-Mar-02	NDT163NR82WSec25	600	0.00
PETERSON 2	0	5-Mar-07	NDT162NR81WSec32	500	0.00
Evenson SWD #1	190	7-Aug-01	NDT162NR81WSec32	485	155.00
	1102	28-Mar-91	NDT161NR82WSec25	480	4.00
Madsen Johnson 21-28#5	20080918131500	6-Sep-08	NDT163NR77WSec27	410	0.36
Madsen Johnson 32-28#3	20080918125300	6-Sep-08	NDT163NR77WSec28	410	0.36
THOMAS HEDGE S3	20120507080200	6-May-12	NDT162NR81WSec30	400	0.00
TRENDSKAADEN 44-282	20091125092700	21-Nov-09	NDT163NR77WSec28	350	0.00
	469	26-Aug-83	NDT163NR83WSec23	330	30.00
A.O.ERICKSON SWD	20110228181000	27-Feb-11	NDT161NR82WSec13	300	0.00
CRAMER 1 SWD	20110721173400	20-Jul-11	NDT161NR82WSec8	300	0.00
FOSSUM B3	20131202095400	27-Nov-13	NDT161NR81WSec29	300	50.00
RICE-STATE 2H	20110225132200	25-Feb-11	NDT161NR82WSec16	300	0.00
	1121	10-May-91	NDT161NR82WSec25	300	8.00
PETERSON 2	20150318082700	17-Mar-15	NDT162NR81WSec32	285	0.00
	1638	23-Sep-95	NDT159NR82WSec13	275	25.00
JESPERSON 31-29	20140730084300	29-Jul-14	NDT163NR82WSec29	260	5.00
Antler Midal Unit CTB	20101116140200	15-Nov-10	NDT163NR82WSec25	250	50.00
CARLO.GILSETHETUX2-R	20140618023900	17-Jun-14	NDT161NR83WSec5	250	0.00
Durnin CTB (Durnin""A""#D01)	2356	31-Dec-03	NDT161NR82WSec25	250	0.00
PEARSON BATTERY	20111105095100	4-Nov-11	NDT163NR83WSec22	250	0.00
ERICKSON ETAL 3B	20120719103500	18-Jul-12	NDT162NR82WSec30	243	0.00
KUROKI MADISON UNIT	20141205142500	5-Dec-14	NDT163NR81WSec12	225	20.00
Fossum B&D Tank Battery	20130314114100	14-Mar-13	NDT161NR81WSec30	200	0.00
Fossum Band DCTB	20110805114900	5-Aug-11	NDT161NR81WSec30	200	0.00
FOSSUMFLB 5-29H	0	6-Jul-10	NDT161NR81WSec29	200	0.00
Haakenstad 22-21#1	2144	24-Jan-03	NDT163NR77WSec21	200	30.00
IVANGEHRINGER 4	20160811094200	9-Aug-16	NDT162NR83WSec31	200	0.00
NEWBURG-SPEARFISH-CHARLES UNIT Q-707-D	20160202104300	30-Sep-15	NDT161NR79WSec22	200	0.00
NORTH WEST HOPE-MADISONUNITGB-2R	20090522095300	16-May-09	NDT164NR80WSec35	200	10.00
	1372	21-Jan-94	NDT162NR81WSec14	200	0.00
	484	21-Apr-83	NDT161NR81WSec19	200	0.00
O'Connell CTB	20090424172400	24-Apr-09	NDT159NR82WSec36	173	0.00
	1840	8-Feb-00	NDT161NR79WSec21	150	0.00
Madsen Johnson 21-28#5	20081124085100	20-Nov-08	NDT163NR77WSec28	125	4.00
LILLIE FARMS PARTNERSHIP S.W.D.1	20120828174800	20-Aug-12	NDT161NR81WSec10	120	10.00
REIQUAM STATE 4	0	16-Jan-06	NDT159NR82WSec36	115	0.00
	1686	3-Mar-96	NDT163NR77WSec21	114	0.00
AMANDAPETERSON31-35	0	15-Mar-05	NDT162NR82WSec35	100	5.00
Bull CTB	20110218090000	18-Feb-11	NDT163NR82WSec23	100	5.00
Cramer#1SWD	2021	10-May-02	NDT161NR82WSec8	100	0.00
CRAMER1SWD	0	16-Apr-07	NDT161NR82WSec8	100	0.00

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Township Range Sections	Salt Water	Oil Volume
Gehringer Unit CTB	20150319151800	14-Mar-15	NDT162NR83WSec31	100	0.00
MONTGOMERY 1	20101019092400	11-Oct-10	NDT162NR80WSec1	100	10.00
MONTGOMERY 1	20101019093400	19-Oct-10	NDT162NR80WSec1	100	5.00
RICE-STATE2H	20140812153300	12-Aug-14	NDT161NR82WSec16	100	0.00
RiceTrust#1	2613	5-Jan-05	NDT161NR82WSec8	100	0.00
Stead44-14#2	20081230155600	29-Dec-08	NDT162NR81WSec14	100	0.00
WRIGHT13-12	0	6-Feb-06	NDT163NR81WSec12	100	5.00
BrandjordCTB	2595	12-Dec-04	NDT163NR78WSec20	98	2.00
	1216	21-Sep-92	NDT161NR82WSec23	98	0.00
KUROKIMADISON UNIT	20150612135200	12-Jun-15	NDT163NR81WSec12	97	3.00
2-BRENDEN9-331-M	20140515145200	14-May-14	NDT164NR77WSec33	95	5.00
CRAMER1SWD	20130429185300	28-Apr-13	NDT161NR82WSec8	91	0.00
NSCU Satellite 5 CTB	20141212205500	12-Dec-14	NDT161NR79WSec17	90	60.00
BRONDERSLEV 6H	20111215105400	15-Dec-11	NDT162NR81WSec32	80	3.00
NSCU CTB	2264	28-Aug-03	NDT161NR79WSec21	80	0.00
Gehringer Unit CTB	20130816132500	16-Aug-13	NDT162NR83WSec31	75	75.00
NSCU Satellite5	2138	14-Jan-03	NDT161NR79WSec8	75	20.00
CLARAMOEN1-33	20140908201100	6-Sep-14	NDT164NR77WSec33	70	0.00
KANE MADISON UNIT CENTRAL BATTERY	20131125170200	24-Nov-13	NDT162NR79WSec35	70	0.00
	1521	6-Dec-94	NDT163NR77WSec21	70	6.00
Witherstine Injection Plant (Witherstine,W.H.#1)	2388	3-Feb-04	NDT161NR82WSec25	62	0.00
ALMONLEE 2	20150422111900	21-Apr-15	NDT162NR80WSec11	60	0.00
M.FOSS1	0	11-Jun-12	NDT162NR82WSec36	60	0.00
NEWBURG-SPEARFISH-CHARLESUNITN-706	20140529161900	29-May-14	NDT161NR79WSec21	60	3.00
	1331	15-Oct-93	NDT163NR77WSec28	60	0.00
	1370	21-Jan-94	NDT163NR78WSec29	60	0.00
Mohall Madison Unit	20130827153700	24-Aug-13	NDT161NR83WSec6	54	2.00
NELSON-SHARON1H	20091013085000	6-Oct-09	NDT159NR82WSec13	53	0.00
ALMONLEE 2	20140727152100	27-Jul-14	NDT162NR80WSec11	50	0.00
BROWNP11-30H	20150424082100	23-Apr-15	NDT161NR81WSec30	50	3.00
CLIFFORD 43-35-R	20090415102500	16-Feb-09	NDT162NR82WSec35	50	0.00
GANDRSIVERTSON 1	20110831123000	30-Aug-11	NDT163NR79WSec8	50	0.00
IVANGEHRINGER T-11	20091002165600	2-Oct-09	NDT162NR83WSec31	50	5.00
KING SWD SYSTEM D 01	20150724143500	24-Jul-15	NDT162NR80WSec24	50	0.00
NEWBURG-SPEARFISH-CHARLESUNITF-724	20090508142300	7-May-09	NDT162NR79WSec31	50	0.00
Reiquam State CTB	0	14-Nov-06	NDT159NR82WSec36	50	0.00
SCANDIACTB	20150221184600	21-Feb-15	NDT164NR78WSec34	50	50.00
SMETANA 311	20100702145900	27-Jun-10	NDT160NR83WSec31	50	5.00
SMETANA 312	20120516144600	12-May-12	NDT160NR83WSec31	50	0.00
	605	1-Feb-82	NDT159NR81WSec30	50	0.00
	1753	15-Dec-96	NDT161NR79WSec21	45	15.00
	1758	15-Dec-96	NDT161NR79WSec21	45	15.00
	1220	5-Oct-92	NDT161NR82WSec23	43	0.00
Adams #R-1	2249	23-Jul-03	NDT161NR82WSec27	40	0.00
CROAKA1	20150406144400	6-Apr-15	NDT162NR80WSec25	40	10.00
GRAVSETHCR	20150707094300	5-Jul-15	NDT164NR79WSec36	40	0.00
HENDERSON-UCLI2	20130617135300	13-Jun-13	NDT163NR80WSec1	40	0.00
HENDERSON-UCLI4	20080227160200	22-Feb-08	NDT163NR80WSec1	40	2.00
KING SWD SYSTEM D 01	20150430143200	30-Apr-15	NDT162NR80WSec24	40	0.00

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Township Range Sections	Salt Water	Oil Volume
NSCU Satellite 10 CTB	20140811170500	11-Aug-14	NDT161NR79WSec23	40	5.00
PEARSON BATTERY	0	20-Apr-05	NDT163NR83WSec27	40	0.00
SIVERTSON 3	20140417133300	16-Apr-14	NDT163NR79WSec8	40	4.00
STATEA 1	20120103155700	2-Jan-12	NDT164NR80WSec36	40	5.00
	1520	21-Nov-94	NDT163NR77WSec21	40	0.00
	1533	4-Jan-95	NDT163NR77WSec28	40	0.00
	1535	18-Jan-95	NDT163NR77WSec28	40	0.00
	1587	29-May-95	NDT162NR81WSec14	40	0.00
	1197	6-Jul-92	NDT161NR79WSec4	40	10.00
	1793	27-Aug-97	NDT161NR79WSec5	40	5.00
	793	27-Aug-97	NDT161NR79WSec5	40	5.00
	1793	27-Aug-97	NDT161NR79WSec5	40	5.00
A O ERICKSON SWD 1	0	26-Oct-05	NDT161NR82WSec13	35	0.00
Gehringer Unit CTB	20130523151100	21-May-13	NDT162NR83WSec31	35	15.00
	1860	26-Apr-00	NDT161NR79WSec9	35	15.00
Steen CTB	20060818153400	17-Aug-06	NDT159NR81WSec31	31	9.00
2-BRENDEN 9-331-M	20151029184800	29-Oct-15	NDT164NR77WSec33	30	0.00
Erickson CTB	0	28-Oct-08	NDT161NR82WSec13	30	10.00
Evenson CTB	20150618150400	18-Jun-15	NDT162NR81WSec31	30	0.00
George Adams CTB	20151119094200	19-Nov-15	NDT160NR82WSec6	30	0.00
Houmann""C""4CTB	0	6-Oct-08	NDT162NR80WSec10	30	10.00
HOWARDNORDMARK2SWD	20090622100300	22-Jun-09	NDT163NR78WSec30	30	0.00
Hultgren1	20121011163800	11-Oct-12	NDT163NR79WSec24	30	5.00
Koehler	20050427131900	23-Apr-05	NDT162NR81WSec23	30	0.00
LEOHALLOF 1	20060221152000	25-Feb-06	NDT163NR82WSec21	30	0.00
NELSON-SHARON1H	20111201133600	21-Nov-11	NDT159NR82WSec13	30	20.00
NSCU#N-716	2066	27-Jul-02	NDT161NR79WSec9	30	5.00
SKARPHOL16-28CTB	20161219184500	18-Dec-16	NDT164NR77WSec28	30	25.00
STEAD24-144SWD	0	3-Oct-12	NDT162NR81WSec14	30	0.00
STEINHAUS CTB	20130725151700	23-Jul-13	NDT162NR81WSec30	30	30.00
	1593	12-Jun-95	NDT163NR77WSec28	30	3.00
	1544	10-Feb-95	NDT159NR82WSec13	30	30.00
A O ERICKSON 3R	20121022112700	19-Oct-12	NDT161NR82WSec14	25	5.00
CAWDORETAL 1	20120119142100	19-Jan-12	NDT164NR78WSec32	25	0.00
Cramer#1 SWD	2579	12-Nov-04	NDT161NR82WSec8	25	5.00
Haakenstad 22-21	20070305125500	11-Jan-07	NDT163NR77WSec21	25	15.00
Haakenstad CTB	0	11-Jan-07	NDT163NR77WSec21	25	15.00
Moen Trust	20080229084400	21-Feb-08	NDT163NR77WSec21	25	2.00
STEINHAUS CTB	20130407192100	7-Apr-13	NDT162NR81WSec30	25	0.00
WM.STEINHAUS 1	20110530124600	29-May-11	NDT162NR81WSec30	25	0.00
	1447	17-May-94	NDT161NR79WSec4	25	0.00
FEDERAL-WILDLIFE1	20130617111300	16-Jun-13	NDT163NR80WSec1	20	0.00
HEDGES 3&4 CTB	20140107105600	7-Jan-14	NDT162NR81WSec30	20	20.00
Newhouse 2R	2612	3-Jan-05	NDT162NR79WSec3	20	0.00
NORTH WEST HOPE MADISON UNIT	20111213161500	12-Dec-11	NDT164NR80WSec36	20	0.00
NORTH WEST HOPE MADISON UNIT	20121213095600	11-Dec-12	NDT164NR80WSec36	20	40.00
NSCU #I-717	87	25-May-01	NDT161NR79WSec8	20	0.00
NSCU Satellite 3 CTB	20130526122000	25-May-13	NDT161NR79WSec7	20	4.00
PETERSON 2	20120827145900	9-Jul-12	NDT162NR81WSec32	20	10.00

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Township Range Sections	Salt Water	Oil Volume
PETERSON 43-4R	20131217131000	7-Dec-13	NDT161NR81WSec4	20	0.00
Wheaton CTB	20140430075900	25-Apr-14	NDT164NR83WSec33	20	2.00
WILEY,T.A.2	20141002082700	1-Oct-14	NDT161NR81WSec19	20	1.00
	1455	27-May-94	NDT163NR77WSec21	20	20.00
	1605	9-Jul-95	NDT163NR77WSec28	20	0.00
	1444	10-May-94	NDT162NR80WSec10	20	0.00
	1734	14-Sep-96	NDT161NR79WSec4	20	0.00
	1345	11-Dec-93	NDT161NR79WSec6	20	1.00
	1893	16-Nov-99	NDT161NR79WSec9	20	1.00
	1554	18-Apr-95	NDT161NR79WSec10	20	10.00
	1090	4-Feb-91	NDT161NR79WSec16	20	22.00
HAAKENSTAD 11-212	20100824142800	24-Aug-10	NDT163NR77WSec21	19	1.00
MARTIN-WILLIAMS SWD1	20130504195900	4-May-13	NDT162NR80WSec27	18	0.00
	444	30-Dec-83	NDT161NR82WSec25	18	20.00
CORINTHIAN LOCHNER 16-331-H	20140506124400	5-May-14	NDT164NR77WSec33	17	3.00
Adams CTB	0	16-Oct-05	NDT161NR82WSec27	15	1.00
AFTEMA 1	20090430100100	29-May-09	NDT163NR78WSec6	15	0.00
EVENSON 1-R	20140627080100	26-Jun-14	NDT162NR81WSec31	15	0.00
GRAVSETHBR	20130311122100	2-Mar-13	NDT164NR79WSec36	15	0.00
HAAKENSTAD 11-212	0	16-Dec-05	NDT163NR77WSec21	15	2.00
Harold Gravseth #1	20071001155400	30-Sep-07	NDT164NR78WSec31	15	2.00
Hedges Tank Battery	20110505212100	5-May-11	NDT162NR81WSec30	15	0.00
Nordmark 31-9	20080522074500	18-May-08	NDT163NR78WSec29	15	0.00
Peterson CTB	20090225094200	4-Jan-09	NDT162NR81WSec32	15	15.00
	1640	17-Oct-95	NDT161NR79WSec9	14	0.00
BACKMAN 15-35	20150914151100	14-Sep-15	NDT164NR77WSec35	12	0.00
ALMONLEE2	20140324133000	24-Mar-14	NDT162NR80WSec11	10	0.00
Federal Wild life	20050731175000	6-Jun-05	NDT163NR80WSec1	10	10.00
Fossum ""A""CTB	20130109162000	9-Jan-13	NDT161NR81WSec30	10	0.00
JESPERSON 31-29	20100723154000	23-Jul-10	NDT163NR82WSec29	10	0.00
JOHN W ADDLE 1-29	20160310163300	31-Dec-15	NDT161NR78WSec29	10	0.00
Madsen Johnson 21-28#5	20070913151900	4-Sep-07	NDT163NR77WSec28	10	0.36
NORTH WEST HOPE-MADISON UNIT C-5	20120423160500	23-Apr-12	NDT163NR80WSec2	10	2.00
NSCUH-722	20131219090900	18-Dec-13	NDT162NR79WSec31	10	0.00
P.M.KING ESTATE 1-A-R	20170412181900	11-Apr-17	NDT162NR80WSec23	10	30.00
PETERSON 2	20111212112300	12-Dec-11	NDT162NR81WSec32	10	0.00
SCANDIA 1-34H	20130113192900	13-Jan-13	NDT164NR78WSec34	10	0.00
SWSCU #30-12	2176	8-Mar-03	NDT162NR79WSec30	10	5.00
Whitherstine Tank Battery	20111228152700	28-Dec-11	NDT161NR82WSec25	10	30.00
WILMS INJECTION PLANT CTB	20110228175100	26-Feb-11	NDT163NR82WSec23	10	0.00
	1401	28-Sep-94	NDT163NR77WSec21	10	0.00
	1441	27-Apr-94	NDT163NR77WSec28	10	0.00
	1569	24-Apr-95	NDT162NR79WSec31	10	0.00
	1872	21-Jun-00	NDT161NR79WSec4	10	1.00
	1382	16-Feb-94	NDT161NR79WSec6	10	4.00
	1780	16-May-97	NDT161NR79WSec10	10	5.00
	1242	5-Dec-92	NDT161NR79WSec16	10	5.00
	1637	25-Sep-95	NDT161NR79WSec16	10	5.00
	1262	19-Jan-93	NDT161NR82WSec24	10	0.00
	618	13-Jan-82	NDT161NR82WSec25	10	20.00

Appendix: C

Mann-Kendall non-Parametric Statistical Analysis Table

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
Nelson #2-13 SWD	2554	9/20/2004	-0.200	0.220	-0.0000041
TRENDSKAADEN 44-282	20110803100400	7/21/2011	-0.076	0.655	-0.0000021
RICE-STATE 2H	20120626171300	6/26/2012	0.152	0.355	0.0000041
Haugen BCTB	20140606093900	6/6/2014	-0.098	0.601	-0.0000027
Madsen CTB	20111201132200	11/19/2011	-0.076	0.655	-0.0000021
Wilms Injection Plant (Wilms)	2362	1/6/2004	-0.111	0.550	-0.0000026
CRAMER1SWD	20121027080900	10/26/2012	0.007	1.000	0.0000002
	1994	3/29/2002	-0.143	0.387	-0.0000043
PETERSON 2	0	3/5/2007	0.038	0.835	0.0000006
Evenson SWD #1	190	8/7/2001	0.038	0.835	0.0000006
	1102	3/28/1991	0.057	0.744	0.0000016
Madsen Johnson 21-28#5	20080918131500	9/6/2008	-0.316	0.055	-0.0000063
Madsen Johnson 32-28#3	20080918125300	9/6/2008	0.053	0.783	0.0000013
THOMAS HEDGE S3	20120507080200	5/6/2012	-0.255	0.152	-0.0000049
TRENDSKAADEN 44-282	20091125092700	11/21/2009	-0.076	0.655	-0.0000021
	469	8/26/1983	0.076	0.655	0.0000026
A.O.ERICKSON SWD	20110228181000	2/27/2011	-0.114	0.493	-0.0000027
CRAMER 1 SWD	20110721173400	7/20/2011	0.007	1.000	0.0000002
FOSSUM B3	20131202095400	11/27/2013	-0.095	0.572	-0.0000031
RICE-STATE 2H	20110225132200	2/25/2011	-0.114	0.493	-0.0000027
	1121	5/10/1991	0.074	0.656	0.0000028
PETERSON 2	20150318082700	3/17/2015	-0.216	0.211	-0.0000055
	1638	9/23/1995	-0.205	0.238	-0.0000045
JESPERSON 31-29	20140730084300	7/29/2014	-0.126	0.435	-0.0000034
Antler Midal Unit CTB	20101116140200	11/15/2010	-0.298	0.080	-0.0000081
CARLO.GILSETHETUX2-R	20140618023900	6/17/2014	-0.216	0.211	-0.0000066
Durnin CTB (Durnin""A""#D01)	2356	12/31/2003	-0.181	0.298	-0.0000056
PEARSON BATTERY	20111105095100	11/4/2011	0.030	0.868	0.0000014
ERICKSON ETAL 3B	20120719103500	7/18/2012	-0.056	0.739	-0.0000016
KUROKI MADISON UNIT	20141205142500	12/5/2014	-0.064	0.730	-0.0000019
Fossum B&D Tank Battery	20130314114100	3/14/2013	0.018	0.945	0.0000002
Fossum Band DCTB	20110805114900	8/5/2011	0.018	0.945	0.0000002
FOSSUMFLB 5-29H	0	7/6/2010	-0.216	0.211	-0.0000047
Haakenstad 22-21#1	2144	1/24/2003	-0.021	0.924	-0.0000008
IVANGEHRINGER 4	20160811094200	8/9/2016	0.039	0.824	0.0000008
NEWBURG-SPEARFISH-CHARLES UNIT Q-707-D	20160202104300	9/30/2015	0.152	0.355	0.0000032
NORTH WEST HOPE-MADISONUNITGB-2R	20090522095300	5/16/2009	-0.004	1.000	-0.0000007
	1372	1/21/1994	0.000	0.976	0.0000002
	484	4/21/1983	-0.088	0.629	-0.0000027
O'Connell CTB	20090424172400	4/24/2009	-0.216	0.229	-0.0000089
	1840	2/8/2000	-0.088	0.629	-0.0000027
Madsen Johnson 21-28#5	20081124085100	11/20/2008	-0.082	0.617	-0.0000024
LILLIE FARMS PARTNERSHIP S.W.D.1	20120828174800	8/20/2012	-0.117	0.469	-0.0000027
REIQUAM STATE 4	0	1/16/2006	-0.126	0.435	-0.0000045
	1686	3/3/1996	-0.021	0.924	-0.0000008
AMANDAPETERSON31-35	0	3/15/2005	-0.221	0.186	-0.0000069
Bull CTB	20110218090000	2/18/2011	-0.160	0.315	-0.0000051
Cramer#1SWD	2021	5/10/2002	-0.086	0.613	-0.0000023
CRAMER1SWD	0	4/16/2007	0.108	0.504	0.0000034

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
Gehringer Unit CTB	20150319151800	3/14/2015	0.039	0.824	0.0000008
MONTGOMERY 1	20101019092400	10/11/2010	0.039	0.824	0.0000008
MONTGOMERY 1	20101019093400	10/19/2010	-0.126	0.435	-0.0000034
RICE-STATE2H	20140812153300	8/12/2014	-0.088	0.629	-0.0000027
RiceTrust#1	2613	1/5/2005	-0.100	0.540	-0.0000023
Stead44-14#2	20081230155600	12/29/2008	0.032	0.873	0.0000007
WRIGHT13-12	0	2/6/2006	-0.064	0.730	-0.0000019
BrandjordCTB	2595	12/12/2004	-0.064	0.730	-0.0000019
	1216	9/21/1992	-0.099	0.581	-0.0000026
KUROKIMADISON UNIT	20150612135200	6/12/2015	-0.064	0.730	-0.0000019
2-BRENDEN9-331-M	20140515145200	5/14/2014	-0.111	0.534	-0.0000033
CRAMER1SWD	20130429185300	4/28/2013	-0.013	0.956	-0.0000001
NSCU Satellite 5 CTB	20141212205500	12/12/2014	-0.088	0.629	-0.0000027
BRONDERSLEV 6H	20111215105400	12/15/2011	0.039	0.824	0.0000008
NSCU CTB	2264	8/28/2003	-0.088	0.629	-0.0000027
Gehringer Unit CTB	20130816132500	8/16/2013	0.039	0.824	0.0000008
NSCU Satellite5	2138	1/14/2003	0.004	1.000	0.0000000
CLARAMOEN1-33	20140908201100	9/6/2014	-0.099	0.581	-0.0000025
KANE MADISON UNIT CENTRAL BATTERY	20131125170200	11/24/2013	-0.193	0.267	-0.0000030
	1521	12/6/1994	-0.158	0.368	-0.0000044
Witherstine Injection Plant (Witherstine,W.H.#1)	2388	2/3/2004	-0.181	0.298	-0.0000056
ALMONLEE 2	20150422111900	4/21/2015	-0.117	0.469	-0.0000035
M.FOSS1	0	6/11/2012	-0.193	0.267	-0.0000030
NEWBURG-SPEARFISH-CHARLESUNITN-706	20140529161900	5/29/2014	0.152	0.355	0.0000032
	1331	10/15/1993	-0.181	0.298	-0.0000048
	1370	1/21/1994	-0.124	0.456	-0.0000033
Mohall Madison Unit	20130827153700	8/24/2013	-0.100	0.540	-0.0000056
NELSON-SHARON1H	20091013085000	10/6/2009	-0.169	0.289	-0.0000038
ALMONLEE 2	20140727152100	7/27/2014	-0.117	0.469	-0.0000035
BROWNP11-30H	20150424082100	4/23/2015	0.018	0.945	0.0000002
CLIFFORD 43-35-R	20090415102500	2/16/2009	-0.193	0.267	-0.0000030
GANDRSIVERTSON 1	20110831123000	8/30/2011	-0.064	0.730	-0.0000019
IVANGEHRINGER T-11	20091002165600	10/2/2009	-0.117	0.469	-0.0000034
KING SWD SYSTEM D 01	20150724143500	7/24/2015	-0.216	0.211	-0.0000066
NEWBURG-SPEARFISH-CHARLESUNITF-724	20090508142300	5/7/2009	-0.004	1.000	-0.0000003
Reiquam State CTB	0	11/14/2006	0.018	0.945	0.0000012
SCANDIACTB	20150221184600	2/21/2015	-0.004	1.000	-0.0000007
SMETANA 311	20100702145900	6/27/2010	-0.205	0.238	-0.0000045
SMETANA 312	20120516144600	5/12/2012	-0.205	0.238	-0.0000045
	605	2/1/1982	-0.086	0.613	-0.0000052
	1753	12/15/1996	0.175	0.322	0.0000046
	1758	12/15/1996	-0.205	0.215	-0.0000030
	1220	10/5/1992	-0.099	0.581	-0.0000026
Adams #R-1	2249	7/23/2003	-0.240	0.164	-0.0000087
CROAKA1	20150406144400	4/6/2015	-0.205	0.238	-0.0000045
GRAVSETHCR	20150707094300	7/5/2015	0.084	0.631	0.0000015
HENDERSON-UCLI2	20130617135300	6/13/2013	-0.170	0.332	-0.0000054
HENDERSON-UCLI4	20080227160200	2/22/2008	0.084	0.631	0.0000015
KING SWD SYSTEM D 01	20150430143200	4/30/2015	0.038	0.835	0.0000011

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
NSCU Satellite 10 CTB	20140811170500	8/11/2014	-0.193	0.267	-0.0000053
PEARSON BATTERY	0	4/20/2005	-0.298	0.080	-0.0000081
SIVERTSON 3	20140417133300	4/16/2014	-0.064	0.730	-0.0000019
STATEA 1	20120103155700	1/2/2012	-0.228	0.186	-0.0000084
	1520	11/21/1994	-0.074	0.656	-0.0000030
	1533	1/4/1995	-0.240	0.164	-0.0000078
	1535	1/18/1995	-0.082	0.617	-0.0000024
	1587	5/29/1995	0.032	0.873	0.0000007
	1197	7/6/1992	-0.170	0.332	-0.0000032
	1793	8/27/1997	0.146	0.406	0.0000047
	793	8/27/1997	-0.322	0.058	-0.0000086
	1793	8/27/1997	-0.064	0.730	-0.0000021
A O ERICKSON SWD 1	0	10/26/2005	-0.117	0.469	-0.0000027
Gehringer Unit CTB	20130523151100	5/21/2013	-0.114	0.493	-0.0000050
	1860	4/26/2000	-0.181	0.298	-0.0000067
Steen CTB	20060818153400	8/17/2006	-0.004	1.000	0.0000000
2-BRENDEN 9-331-M	20151029184800	10/29/2015	-0.099	0.581	-0.0000025
Erickson CTB	0	10/28/2008	-0.117	0.469	-0.0000027
Evenson CTB	20150618150400	6/18/2015	0.039	0.824	0.0000008
George Adams CTB	20151119094200	11/19/2015	-0.205	0.238	-0.0000045
Houmann""C""4CTB	0	10/6/2008	-0.065	0.697	-0.0000030
HOWARDNORDMARK2SWD	20090622100300	6/22/2009	-0.126	0.435	-0.0000034
Hultgren1	20121011163800	10/11/2012	-0.160	0.315	-0.0000051
Koehler	20050427131900	4/23/2005	0.038	0.835	0.0000011
LEOHALLOF 1	20060221152000	2/25/2006	-0.116	0.501	-0.0000021
NELSON-SHARON1H	20111201133600	11/21/2011	-0.086	0.613	-0.0000052
NSCU#N-716	2066	7/27/2002	-0.181	0.298	-0.0000067
SKARPHOL16-28CTB	20161219184500	12/18/2016	-0.111	0.534	-0.0000033
STEAD24-144SWD	0	10/3/2012	0.038	0.835	0.0000011
STEINHAUS CTB	20130725151700	7/23/2013	-0.056	0.739	-0.0000016
	1593	6/12/1995	-0.082	0.617	-0.0000024
	1544	2/10/1995	-0.205	0.238	-0.0000045
A O ERICKSON 3R	20121022112700	10/19/2012	-0.053	0.783	-0.0000008
CAWDORETAL 1	20120119142100	1/19/2012	-0.111	0.534	-0.0000033
Cramer#1 SWD	2579	11/12/2004	0.004	1.000	0.0000000
Haakenstad 22-21	20070305125500	1/11/2007	-0.067	0.703	-0.0000009
Haakenstad CTB	0	1/11/2007	-0.076	0.648	-0.0000017
Moen Trust	20080229084400	2/21/2008	-0.018	0.945	0.0000000
STEINHAUS CTB	20130407192100	4/7/2013	-0.056	0.739	-0.0000016
WM.STEINHAUS 1	20110530124600	5/29/2011	0.048	0.781	0.0000017
	1447	5/17/1994	-0.170	0.332	-0.0000032
FEDERAL-WILDLIFE1	20130617111300	6/16/2013	-0.170	0.332	-0.0000054
HEDGES 3&4 CTB	20140107105600	1/7/2014	-0.056	0.739	-0.0000016
Newhouse 2R	2612	1/3/2005	-0.065	0.697	-0.0000030
NORTH WEST HOPE MADISON UNIT	20111213161500	12/12/2011	-0.074	0.677	-0.0000027
NORTH WEST HOPE MADISON UNIT	20121213095600	12/11/2012	-0.263	0.125	-0.0000090
NSCU #I-717	87	5/25/2001	-0.158	0.368	-0.0000051
NSCU Satellite 3 CTB	20130526122000	5/25/2013	-0.158	0.368	-0.0000051
PETERSON 2	20120827145900	7/9/2012	0.039	0.824	0.0000008

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
PETERSON 43-4R	20131217131000	12/7/2013	-0.216	0.211	-0.0000066
Wheaton CTB	20140430075900	4/25/2014	-0.111	0.534	-0.0000033
WILEY,T.A.2	20141002082700	10/1/2014	-0.088	0.629	-0.0000027
	1455	5/27/1994	-0.064	0.730	-0.0000019
	1605	7/9/1995	-0.082	0.617	-0.0000024
	1444	5/10/1994	-0.065	0.697	-0.0000030
	1734	9/14/1996	-0.048	0.781	-0.0000010
	1345	12/11/1993	-0.158	0.368	-0.0000051
	1893	11/16/1999	-0.181	0.298	-0.0000067
	1554	4/18/1995	-0.181	0.298	-0.0000067
	1090	2/4/1991	-0.099	0.581	-0.0000024
HAAKENSTAD 11-212	20100824142800	8/24/2010	-0.211	0.209	-0.0000090
MARTIN-WILLIAMS SWD1	20130504195900	5/4/2013	-0.205	0.238	-0.0000045
	444	12/30/1983	-0.030	0.868	-0.0000010
CORINTHIAN LOCHNER 16-331-H	20140506124400	5/5/2014	-0.111	0.534	-0.0000033
Adams CTB	0	10/16/2005	-0.240	0.164	-0.0000087
AFTEMA 1	20090430100100	5/29/2009	-0.134	0.403	-0.0000028
EVENSON 1-R	20140627080100	6/26/2014	0.039	0.824	0.0000008
GRAVSETHBR	20130311122100	3/2/2013	-0.263	0.125	-0.0000090
HAAKENSTAD 11-212	0	12/16/2005	-0.048	0.781	-0.0000019
Harold Gravseth #1	20071001155400	9/30/2007	-0.111	0.534	-0.0000033
Hedges Tank Battery	20110505212100	5/5/2011	-0.205	0.238	-0.0000045
Nordmark 31-9	20080522074500	5/18/2008	-0.082	0.617	-0.0000024
Peterson CTB	20090225094200	1/4/2009	0.039	0.824	0.0000008
	1640	10/17/1995	-0.181	0.298	-0.0000067
BACKMAN 15-35	20150914151100	9/14/2015	-0.228	0.186	-0.0000084
ALMONLEE2	20140324133000	3/24/2014	-0.117	0.469	-0.0000035
Federal Wild life	20050731175000	6/6/2005	0.084	0.631	0.0000015
Fossum ""A""CTB	20130109162000	1/9/2013	0.018	0.945	0.0000002
JESPERSON 31-29	20100723154000	7/23/2010	-0.099	0.581	-0.0000013
JOHN W ADDLE 1-29	20160310163300	12/31/2015	-0.057	0.744	-0.0000027
Madsen Johnson 21-28#5	20070913151900	9/4/2007	-0.082	0.617	-0.0000024
NORTH WEST HOPE-MADISON UNIT C-5	20120423160500	4/23/2012	0.029	0.890	0.0000006
NSCUH-722	20131219090900	12/18/2013	0.039	0.824	0.0000008
P.M.KING ESTATE 1-A-R	20170412181900	4/11/2017	0.038	0.835	0.0000011
PETERSON 2	20111212112300	12/12/2011	0.190	0.244	0.0000044
SCANDIA 1-34H	20130113192900	1/13/2013	-0.099	0.581	-0.0000025
SWSCU #30-12	2176	3/8/2003	-0.205	0.238	-0.0000045
Whitherstine Tank Battery	20111228152700	12/28/2011	-0.123	0.489	-0.0000023
WILMS INJECTION PLANT CTB	20110228175100	2/26/2011	-0.160	0.315	-0.0000051
	1401	9/28/1994	-0.048	0.781	-0.0000011
	1441	4/27/1994	-0.181	0.298	-0.0000048
	1569	4/24/1995	-0.195	0.219	-0.0000083
	1872	6/21/2000	-0.048	0.781	-0.0000010
	1382	2/16/1994	-0.158	0.368	-0.0000051
	1780	5/16/1997	-0.117	0.469	-0.0000027
	1242	12/5/1992	0.143	0.372	0.0000040
	1637	9/25/1995	0.143	0.372	0.0000040
	1262	1/19/1993	-0.039	0.824	-0.0000044
	618	1/13/1982	-0.030	0.868	-0.0000010

Appendix: D

Regression Analysis

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
Nelson #2-13 SWD	2554	9/20/2004	y = -3E-06x + 0.9137	R² = 0.0307	0.0000061
TRENDSKAADEN 44-282	20110803100400	7/21/2011	y = -1E-06x + 0.8558	R² = 0.0095	0.0000013
RICE-STATE 2H	20120626171300	6/26/2012	y = 5E-06x + 0.6201	R² = 0.1033	0.0000391
Haugen BCTB	20140606093900	6/6/2014	y = -2E-06x + 0.8307	R² = 0.0197	0.1334977
Madsen CTB	20111201132200	11/19/2011	y = -1E-06x + 0.8558	R² = 0.0095	0.0000013
Wilms Injection Plant (Wilms)	2362	1/6/2004	y = -3E-06x + 0.8875	R² = 0.0353	0.1261546
CRAMER1SWD	20121027080900	10/26/2012	y = 6E-07x + 0.7839	R² = 0.0022	0.1722032
	1994	3/29/2002	y = -4E-06x + 0.9467	R² = 0.0348	0.0000942
PETERSON 2	0	3/5/2007	y = 1E-06x + 0.7492	R² = 0.0058	0.0000030
Evenson SWD #1	190	8/7/2001	y = 1E-06x + 0.7492	R² = 0.0058	0.0000030
	1102	3/28/1991	y = 1E-06x + 0.7434	R² = 0.0023	0.0027885
Madsen Johnson 21-28#5	20080918131500	9/6/2008	y = -6E-06x + 1.0352	R² = 0.2001	0.0081374
Madsen Johnson 32-28#3	20080918125300	9/6/2008	y = 3E-08x + 0.8122	R² = 3E-06	0.2237642
THOMAS HEDGE S3	20120507080200	5/6/2012	y = -6E-06x + 1.0324	R² = 0.2283	0.0903687
TRENDSKAADEN 44-282	20091125092700	11/21/2009	y = -1E-06x + 0.8558	R² = 0.0095	0.0000013
	469	8/26/1983	y = 5E-06x + 0.5786	R² = 0.0351	0.0092659
A.O.ERICKSON SWD	20110228181000	2/27/2011	y = -6E-06x + 0.9702	R² = 0.0242	0.0065852
CRAMER 1 SWD	20110721173400	7/20/2011	y = 6E-07x + 0.7839	R² = 0.0022	0.1722032
FOSSUM B3	20131202095400	11/27/2013	y = -2E-06x + 0.831	R² = 0.0063	0.0001045
RICE-STATE 2H	20110225132200	2/25/2011	y = 5E-06x + 0.6201	R² = 0.1033	0.0000391
	1121	5/10/1991	y = 1E-06x + 0.7415	R² = 0.0025	0.0027885
PETERSON 2	20150318082700	3/17/2015	y = -3E-06x + 0.8655	R² = 0.0152	0.1353036
	1638	9/23/1995	y = -4E-06x + 0.9044	R² = 0.1178	0.1052752
JESPERSON 31-29	20140730084300	7/29/2014	y = -4E-06x + 0.8832	R² = 0.0276	0.0003858
Antler Midal Unit CTB	20101116140200	11/15/2010	y = -1E-05x + 1.1585	R² = 0.2893	0.0599413
CARLO.GILSETHETUX2-R	20140618023900	6/17/2014	y = -4E-06x + 0.9423	R² = 0.0579	0.1167884
Durnin CTB (Durnin""A""#D01)	2356	12/31/2003	y = -4E-06x + 0.8982	R² = 0.0426	0.1186906
PEARSON BATTERY	20111105095100	11/4/2011	y = 4E-06x + 0.6111	R² = 0.0232	0.0092659
ERICKSON ETAL 3B	20120719103500	7/18/2012	y = -1E-06x + 0.821	R² = 0.0024	0.0008433
KUROKI MADISON UNIT	20141205142500	12/5/2014	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
Fossum B&D Tank Battery	20130314114100	3/14/2013	y = 3E-06x + 0.6168	R² = 0.0256	0.2235959
Fossum Band DCTB	20110805114900	8/5/2011	y = 3E-06x + 0.6168	R² = 0.0256	0.2235959
FOSSUMFLB 5-29H	0	7/6/2010	y = -6E-06x + 0.9803	R² = 0.0395	0.1054400
Haakenstad 22-21#1	2144	1/24/2003	y = -1E-06x + 0.8136	R² = 0.0053	0.2810401
IVANGEHRINGER 4	20160811094200	8/9/2016	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030
NEWBURG-SPEARFISH-CHARLES UNIT Q-707-D	20160202104300	9/30/2015	y = 3E-06x + 0.6838	R² = 0.043	0.2445501
NORTH WEST HOPE-MADISONUNITGB-2R	20090522095300	5/16/2009	y = 4E-07x + 0.7636	R² = 0.0003	0.0010444
	1372	1/21/1994	y = 1E-06x + 0.7831	R² = 0.0058	0.9347280
	484	4/21/1983	y = -2E-06x + 0.8566	R² = 0.0155	0.1384836
O'Connell CTB	20090424172400	4/24/2009	y = -6E-06x + 0.9792	R² = 0.0611	0.4246421
	1840	2/8/2000	y = -2E-06x + 0.8566	R² = 0.0155	0.1384836
Madsen Johnson 21-28#5	20081124085100	11/20/2008	y = -2E-06x + 0.8705	R² = 0.0136	0.0000013
LILLIE FARMS PARTNERSHIP S.W.D.1	20120828174800	8/20/2012	y = -6E-06x + 0.984	R² = 0.0266	0.0065852
REIQUAM STATE 4	0	1/16/2006	y = -5E-06x + 0.9652	R² = 0.0554	0.0000730
	1686	3/3/1996	y = -1E-06x + 0.8136	R² = 0.0053	0.2810401
AMANDAPETERSON31-35	0	3/15/2005	y = -6E-06x + 1.0222	R² = 0.1038	0.1702009
Bull CTB	20110218090000	2/18/2011	y = -5E-06x + 0.9674	R² = 0.0407	0.0000942
Cramer#1SWD	2021	5/10/2002	y = -2E-06x + 0.8416	R² = 0.0109	0.1723408
CRAMER1SWD	0	4/16/2007	y = 3E-06x + 0.6686	R² = 0.0088	0.0210577
Gehringer Unit CTB	20150319151800	3/14/2015	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
MONTGOMERY 1	20101019092400	10/11/2010	y = -4E-07x + 0.8094	R² = 0.0005	0.1625004
MONTGOMERY 1	20101019093400	10/19/2010	y = -4E-06x + 0.8832	R² = 0.0276	0.0003858
RICE-STATE2H	20140812153300	8/12/2014	y = -2E-06x + 0.8566	R² = 0.0155	0.1384836
RiceTrust#1	2613	1/5/2005	y = -2E-06x + 0.839	R² = 0.0156	0.0000424
Stead44-14#2	20081230155600	12/29/2008	y = 8E-08x + 0.822	R² = 5E-05	0.3094312
WRIGHT13-12	0	2/6/2006	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
BrandjordCTB	2595	12/12/2004	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
	1216	9/21/1992	y = -3E-06x + 0.8889	R² = 0.0363	0.1261546
KUROKIMADISON UNIT	20150612135200	6/12/2015	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
2-BRENDEN9-331-M	20140515145200	5/14/2014	y = -4E-06x + 0.932	R² = 0.0492	0.1113975
CRAMER1SWD	20130429185300	4/28/2013	y = -8E-07x + 0.8264	R² = 0.0015	0.0002397
NSCU Satellite 5 CTB	20141212205500	12/12/2014	y = -2E-06x + 0.8566	R² = 0.0155	0.1384836
BRONDERSLEV 6H	20111215105400	12/15/2011	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030
NSCU CTB	2264	8/28/2003	y = -2E-06x + 0.8566	R² = 0.0155	0.1384836
Gehringer Unit CTB	20130816132500	8/16/2013	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030
NSCU Satellite5	2138	1/14/2003	y = -1E-06x + 0.8085	R² = 0.0024	0.0002136
CLARAMOEN1-33	20140908201100	9/6/2014	y = -2E-06x + 0.7919	R² = 0.0104	0.1408915
KANE MADISON UNIT CENTRAL BATTERY	20131125170200	11/24/2013	y = -4E-06x + 0.9441	R² = 0.0673	0.1154955
	1521	12/6/1994	y = -6E-06x + 0.9994	R² = 0.0871	0.0979050
Witherstine Injection Plant (Witherstine,W.H.#1)	2388	2/3/2004	y = -4E-06x + 0.8982	R² = 0.0426	0.1186906
ALMONLEE 2	20150422111900	4/21/2015	y = -4E-06x + 0.9167	R² = 0.0327	0.0001773
M.FOSS1	0	6/11/2012	y = -4E-06x + 0.9441	R² = 0.0673	0.1154955
NEWBURG-SPEARFISH-CHARLESUNITN-706	20140529161900	5/29/2014	y = 3E-06x + 0.6838	R² = 0.043	0.2445501
	1331	10/15/1993	y = -4E-06x + 0.9469	R² = 0.1054	0.1067976
	1370	1/21/1994	y = -2E-06x + 0.8697	R² = 0.0184	0.8817607
Mohall Madison Unit	20130827153700	8/24/2013	y = -2E-06x + 0.8491	R² = 0.0046	0.0010584
NELSON-SHARON1H	20091013085000	10/6/2009	y = -3E-06x + 0.8999	R² = 0.0245	0.0000061
ALMONLEE 2	20140727152100	7/27/2014	y = -4E-06x + 0.9167	R² = 0.0327	0.0001773
BROWNP11-30H	20150424082100	4/23/2015	y = 3E-06x + 0.6168	R² = 0.0256	0.2235959
CLIFFORD 43-35-R	20090415102500	2/16/2009	y = -4E-06x + 0.9441	R² = 0.0673	0.1154955
GANDRSIVERTSON 1	20110831123000	8/30/2011	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
IVANGEHRINGER T-11	20091002165600	10/2/2009	y = -2E-06x + 0.8486	R² = 0.0121	0.0002536
KING SWD SYSTEM D 01	20150724143500	7/24/2015	y = -4E-06x + 0.9423	R² = 0.0579	0.1167884
NEWBURG-SPEARFISH-CHARLESUNITF-724	20090508142300	5/7/2009	y = 6E-06x + 0.5092	R² = 0.0361	0.0918968
Reiquam State CTB	0	11/14/2006	y = -4E-08x + 0.7468	R² = 4E-06	0.1731574
SCANDIACTB	20150221184600	2/21/2015	y = 4E-07x + 0.7636	R² = 0.0003	0.0010444
SMETANA 311	20100702145900	6/27/2010	y = -4E-06x + 0.9044	R² = 0.1178	0.1052752
SMETANA 312	20120516144600	5/12/2012	y = -4E-06x + 0.9044	R² = 0.1178	0.1052752
	605	2/1/1982	y = -4E-06x + 0.917	R² = 0.0402	0.0519948
	1753	12/15/1996	y = 4E-06x + 0.6689	R² = 0.0402	0.9531758
	1758	12/15/1996	y = -3E-06x + 0.8963	R² = 0.0777	0.6124859
	1220	10/5/1992	y = -3E-06x + 0.8889	R² = 0.0363	0.1261546
Adams #R-1	2249	7/23/2003	y = -1E-05x + 1.1737	R² = 0.2093	0.0582277
CROAKA1	20150406144400	4/6/2015	y = -5E-06x + 0.9676	R² = 0.1277	0.1036171
GRAVSETHCR	20150707094300	7/5/2015	y = 3E-06x + 0.6925	R² = 0.0514	0.4216591
HENDERSON-UCLI2	20130617135300	6/13/2013	y = -5E-06x + 1.0035	R² = 0.0914	0.0996170
HENDERSON-UCLI4	20080227160200	2/22/2008	y = 3E-06x + 0.6925	R² = 0.0514	0.4216591

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
KING SWD SYSTEM D 01	20150430143200	4/30/2015	y = 7E-07x + 0.8017	R² = 0.0016	0.1767680
NSCU Satellite 10 CTB	20140811170500	8/11/2014	y = -5E-06x + 0.9672	R² = 0.0644	0.1035745
PEARSON BATTERY	0	4/20/2005	y = -1E-05x + 1.1585	R² = 0.2893	0.0599413
SIVERTSON 3	20140417133300	4/16/2014	y = 3E-06x + 0.6854	R² = 0.0132	0.2193676
STATEA 1	20120103155700	1/2/2012	y = -7E-06x + 1.0282	R² = 0.1183	0.0873552
	1520	11/21/1994	y = 2E-06x + 0.6823	R² = 0.0038	0.0214019
	1533	1/4/1995	y = -8E-06x + 1.0852	R² = 0.1601	0.0774641
	1535	1/18/1995	y = -2E-06x + 0.8705	R² = 0.0136	0.0000013
	1587	5/29/1995	y = 8E-08x + 0.822	R² = 5E-05	0.3094312
	1197	7/6/1992	y = -3E-06x + 0.9308	R² = 0.0783	0.1228412
	1793	8/27/1997	y = -4E-07x + 0.7661	R² = 0.0002	0.1753171
	793	8/27/1997	y = -9E-06x + 1.1135	R² = 0.1509	0.1362888
	1793	8/27/1997	y = 2E-06x + 0.6648	R² = 0.0073	0.4292058
A O ERICKSON SWD 1	0	10/26/2005	y = -6E-06x + 0.984	R² = 0.0266	0.0065852
Gehringer Unit CTB	20130523151100	5/21/2013	y = 2E-07x + 0.7055	R² = 4E-05	0.2687398
	1860	4/26/2000	y = -6E-06x + 1.0188	R² = 0.1065	0.0939541
Steen CTB	20060818153400	8/17/2006	y = -4E-06x + 0.9147	R² = 0.0135	0.0058349
2-BRENDEN 9-331-M	20151029184800	10/29/2015	y = -2E-06x + 0.7919	R² = 0.0104	0.1408915
Erickson CTB	0	10/28/2008	y = -6E-06x + 0.984	R² = 0.0266	0.0065852
Evenson CTB	20150618150400	6/18/2015	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030
George Adams CTB	20151119094200	11/19/2015	y = -4E-06x + 0.9044	R² = 0.1178	0.1052752
Houmann""C""4CTB	0	10/6/2008	y = -3E-06x + 0.8477	R² = 0.0087	0.0018571
HOWARDNORDMARK2SWD	20090622100300	6/22/2009	y = -4E-06x + 0.8832	R² = 0.0276	0.0003858
Hultgren1	20121011163800	10/11/2012	y = -5E-06x + 0.9674	R² = 0.0407	0.0000942
Koehler	20050427131900	4/23/2005	y = 7E-07x + 0.8017	R² = 0.0016	0.1767680
LEOHALLOF 1	20060221152000	2/25/2006	y = -4E-06x + 0.9406	R² = 0.0413	0.2183523
NELSON-SHARON1H	20111201133600	11/21/2011	y = -4E-06x + 0.917	R² = 0.0402	0.0519948
NSCU#N-716	2066	7/27/2002	y = -6E-06x + 1.0188	R² = 0.1065	0.0939541
SKARPHOL16-28CTB	20161219184500	12/18/2016	y = -4E-06x + 0.932	R² = 0.0492	0.1113975
STEAD24-144SWD	0	10/3/2012	y = 7E-07x + 0.8017	R² = 0.0016	0.1767680
STEINHAUS CTB	20130725151700	7/23/2013	y = -1E-06x + 0.821	R² = 0.0024	0.0008433
	1593	6/12/1995	y = -2E-06x + 0.8705	R² = 0.0136	0.0000013
	1544	2/10/1995	y = -4E-06x + 0.9044	R² = 0.1178	0.1052752
A O ERICKSON 3R	20121022112700	10/19/2012	y = -1E-06x + 0.8629	R² = 0.0135	0.1468305
CAWDORETAL 1	20120119142100	1/19/2012	y = -4E-06x + 0.932	R² = 0.0492	0.1113975
Cramer#1 SWD	2579	11/12/2004	y = -1E-06x + 0.8085	R² = 0.0024	0.0002136
Haakenstad 22-21	20070305125500	1/11/2007	y = 2E-06x + 0.7236	R² = 0.0111	0.9895223
Haakenstad CTB	0	1/11/2007	y = -7E-07x + 0.8258	R² = 0.0021	0.7291639
Moen Trust	20080229084400	2/21/2008	y = -6E-07x + 0.8398	R² = 0.0026	0.1542009
STEINHAUS CTB	20130407192100	4/7/2013	y = -1E-06x + 0.821	R² = 0.0024	0.0008433
WM.STEINHAUS 1	20110530124600	5/29/2011	y = 4E-06x + 0.6223	R² = 0.0403	0.0011805
	1447	5/17/1994	y = -3E-06x + 0.9308	R² = 0.0783	0.1228412
FEDERAL-WILDLIFE1	20130617111300	6/16/2013	y = -5E-06x + 1.0035	R² = 0.0914	0.0996170
HEDGES 3&4 CTB	20140107105600	1/7/2014	y = -1E-06x + 0.821	R² = 0.0024	0.0008433
Newhouse 2R	2612	1/3/2005	y = -3E-06x + 0.8477	R² = 0.0087	0.0018571
NORTH WEST HOPE MADISON UNIT	20111213161500	12/12/2011	y = 3E-06x + 0.7081	R² = 0.0171	0.9236377
NORTH WEST HOPE MADISON UNIT	20121213095600	12/11/2012	y = -9E-06x + 1.0942	R² = 0.1452	0.0709064
NSCU #I-717	87	5/25/2001	y = 5E-07x + 0.7326	R² = 0.0005	0.1876630
NSCU Satellite 3 CTB	20130526122000	5/25/2013	y = 5E-07x + 0.7326	R² = 0.0005	0.1876630
PETERSON 2	20120827145900	7/9/2012	y = 8E-07x + 0.7603	R² = 0.0034	0.0000030

Oil Facilities Names (As Described)	Incident ID	Date of Incident	Kendall's Tau	Kendall's P-value	Sen's Slope Value
PETERSON 43-4R	20131217131000	12/7/2013	y = -4E-06x + 0.9423	R^2 = 0.0579	0.1167884
Wheaton CTB	20140430075900	4/25/2014	y = -4E-06x + 0.932	R^2 = 0.0492	0.1113975
WILEY,T.A.2	20141002082700	10/1/2014	y = -2E-06x + 0.8566	R^2 = 0.0155	0.1384836
	1455	5/27/1994	y = 3E-06x + 0.6854	R^2 = 0.0132	0.2193676
	1605	7/9/1995	y = -2E-06x + 0.8705	R^2 = 0.0136	0.0000013
	1444	5/10/1994	y = -3E-06x + 0.8477	R^2 = 0.0087	0.0018571
	1734	9/14/1996	y = -6E-07x + 0.7805	R^2 = 0.0005	0.0009858
	1345	12/11/1993	y = 5E-07x + 0.7326	R^2 = 0.0005	0.1876630
	1893	11/16/1999	y = -6E-06x + 1.0188	R^2 = 0.1065	0.0939541
	1554	4/18/1995	y = -6E-06x + 1.0188	R^2 = 0.1065	0.0939541
	1090	2/4/1991	y = -3E-06x + 0.9028	R^2 = 0.0401	0.1260803
HAAKENSTAD 11-212	20100824142800	8/24/2010	y = -6E-06x + 1.0266	R^2 = 0.039	0.9470425
MARTIN-WILLIAMS SWD1	20130504195900	5/4/2013	y = -5E-06x + 0.9676	R^2 = 0.1277	0.1036171
	444	12/30/1983	y = -3E-07x + 0.7812	R^2 = 0.0001	0.0005345
CORINTHIAN LOCHNER 16-331-H	20140506124400	5/5/2014	y = -4E-06x + 0.932	R^2 = 0.0492	0.1113975
Adams CTB	0	10/16/2005	y = -1E-05x + 1.1737	R^2 = 0.2093	0.0582277
AFTEMA 1	20090430100100	5/29/2009	y = -7E-06x + 1.0588	R^2 = 0.0593	0.0004037
EVENSON 1-R	20140627080100	6/26/2014	y = 8E-07x + 0.7603	R^2 = 0.0034	0.0000030
GRAVSETHBR	20130311122100	3/2/2013	y = -9E-06x + 1.0942	R^2 = 0.1452	0.0709064
HAAKENSTAD 11-212	0	12/16/2005	y = -3E-06x + 0.8784	R^2 = 0.0163	0.0000618
Harold Gravseth #1	20071001155400	9/30/2007	y = -4E-06x + 0.932	R^2 = 0.0492	0.1113975
Hedges Tank Battery	20110505212100	5/5/2011	y = -5E-06x + 0.9676	R^2 = 0.1277	0.1036171
Nordmark 31-9	20080522074500	5/18/2008	y = -2E-06x + 0.8705	R^2 = 0.0136	0.0000013
Peterson CTB	20090225094200	1/4/2009	y = 8E-07x + 0.7603	R^2 = 0.0034	0.0000030
	1640	10/17/1995	y = -6E-06x + 1.0188	R^2 = 0.1065	0.0939541
BACKMAN 15-35	20150914151100	9/14/2015	y = -7E-06x + 1.0282	R^2 = 0.1183	0.0873552
ALMONLEE2	20140324133000	3/24/2014	y = -4E-06x + 0.9167	R^2 = 0.0327	0.0001773
Federal Wild life	20050731175000	6/6/2005	y = 3E-06x + 0.6925	R^2 = 0.0514	0.4216591
Fossum ""A""CTB	20130109162000	1/9/2013	y = 3E-06x + 0.6168	R^2 = 0.0256	0.2235959
JESPERSON 31-29	20100723154000	7/23/2010	y = -1E-06x + 0.8721	R^2 = 0.011	0.1463403
JOHN W ADDLE 1-29	20160310163300	12/31/2015	y = -1E-06x + 0.8198	R^2 = 0.0019	0.1803113
Madsen Johnson 21-28#5	20070913151900	9/4/2007	y = -2E-06x + 0.8705	R^2 = 0.0136	0.0000013
NORTH WEST HOPE-MADISON UNIT C-5	20120423160500	4/23/2012	y = -1E-07x + 0.7348	R^2 = 2E-05	0.1853670
NSCUH-722	20131219090900	12/18/2013	y = 8E-07x + 0.7603	R^2 = 0.0034	0.0000030
P.M.KING ESTATE 1-A-R	20170412181900	4/11/2017	y = 7E-07x + 0.8017	R^2 = 0.0016	0.1767680
PETERSON 2	20111212112300	12/12/2011	y = 5E-06x + 0.5676	R^2 = 0.1257	0.6656277
SCANDIA 1-34H	20130113192900	1/13/2013	y = -2E-06x + 0.7919	R^2 = 0.0104	0.1408915
SWSCU #30-12	2176	3/8/2003	y = -5E-06x + 0.9676	R^2 = 0.1277	0.1036171
Whitherstine Tank Battery	20111228152700	12/28/2011	y = -4E-06x + 0.9066	R^2 = 0.0516	0.1166215
WILMS INJECTION PLANT CTB	20110228175100	2/26/2011	y = -5E-06x + 0.9674	R^2 = 0.0407	0.0000942
	1401	9/28/1994	y = -3E-06x + 0.8928	R^2 = 0.0138	0.0001348
	1441	4/27/1994	y = -4E-06x + 0.9469	R^2 = 0.1054	0.1067976
	1569	4/24/1995	y = -6E-06x + 1.0222	R^2 = 0.0805	0.0000095
	1872	6/21/2000	y = -6E-07x + 0.7805	R^2 = 0.0005	0.0009858
	1382	2/16/1994	y = 5E-07x + 0.7326	R^2 = 0.0005	0.1876630
	1780	5/16/1997	y = -6E-06x + 0.984	R^2 = 0.0266	0.0065852
	1242	12/5/1992	y = 5E-06x + 0.6207	R^2 = 0.1037	0.0000391
	1637	9/25/1995	y = 5E-06x + 0.6207	R^2 = 0.1037	0.0000391
	1262	1/19/1993	y = -3E-06x + 0.8991	R^2 = 0.0181	0.0000391
	618	1/13/1982	y = -3E-07x + 0.7812	R^2 = 0.0001	0.0005345